Mechanisms Engineering Test Loop – Phase I Status Report – FY2018 (Update to FY2017 Report)

Nuclear Science and Engineering Division

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Mechanisms Engineering Test Loop– Phase I Status Report – FY2018 (Update to FY2017 Report)

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1   EXECUTIVE SUMMARY

This report documents the current status of the Mechanisms Engineering Test Loop (METL) as of August 2018. Currently, METL has completed Phase I construction, performed an initial heat-up of the METL piping, vessels, and components, baked out the facility under vacuum (minus the test vessels), addressed a variety of punchlist items, transferred sodium from 15 55-gallon drums to the dump tank, in the final commissioning/operations stage.

1.1 Purpose & Background

When fully operational, the METL facility will test small to intermediate-scale components and systems in order to develop advanced liquid metal technologies. Testing different components in METL is essential for the future of advanced fast reactors as it should provide invaluable performance data and reduce the risk of failures during plant operation.

METL also provides development opportunities for younger scientists, engineers, and designers who will ultimately lead the advancement of U.S. liquid metal technologies. The hands-on experience with METL, both successes and perceived failures; will ultimately lead to better liquid metal technology programs that can support the commercialization of advanced reactors.

Some examples of technologies that can be tested in METL include:

1. *Components of an advanced fuel handling system* – Fuel handling systems are used for the insertion and removal of core assemblies located within the reactor vessel. Undoubtedly, these components are essential to the successful operation of fast reactors. For liquid metal applications, fuel handling systems need to work inside the primary vessel and typically penetrate through the cover gas of the primary system. As a result, fuel handling systems must address issues associated with 'sodium-frost' buildup.

2. *Mechanisms for self-actuated control and shutdown systems* – These components have been conceived by various designers to provide added defense-in-depth for reducing the consequences of beyond-design-basis accidents. These self-actuated control and shutdown mechanisms include devices such as curie-point magnets and fusible linkages.

3. *Advanced sensors and instrumentation* – Advanced fast reactors contain sensors and instrumentation for monitoring the condition of the plant. Sometimes these components are required to work while immersed in the primary coolant. This category includes but is not limited to, sensors for the rapid detection of hydrogen presence in sodium (which is indicative of a leak), the detection of impurities in the coolant (i.e., improvement of plugging meters or oxygen sensors), alternative methods of leak detection, improved sensors for level measurement and other advanced sensors or instrumentation that improve the overall performance of the advanced reactor system.

4. *In-service inspection and repair technologies* – These systems include visualization sensors for immersed coolant applications and technologies for the welding and repair of structures in contact with the primary coolant.

5. *Thermal hydraulic testing in prototypic sodium environment* – A thermal hydraulic test loop could be used to acquire distributed temperature data in the cold and hot pools of a small scale sodium fast reactor during simulated nominal and protected/unprotected loss

of flow accidents. This testing could allow for the articulation of the heated region in the core to allow for a parametric study of IHX/core outlet height difference and its effect on thermal stratification of sodium in the hot pool. Ultimately this data will be used for validating CFD and systems level code.

As shown below in Figure 1, the design of the METL facility consists of a number of test vessels connected in parallel to a main sodium loop. The different vessels share an expansion tank, purification system, and several electromagnetic (EM) pumps and flowmeters. This flexible, consolidated design minimizes infrastructure requirements and allows multiple experiments to be performed simultaneously.
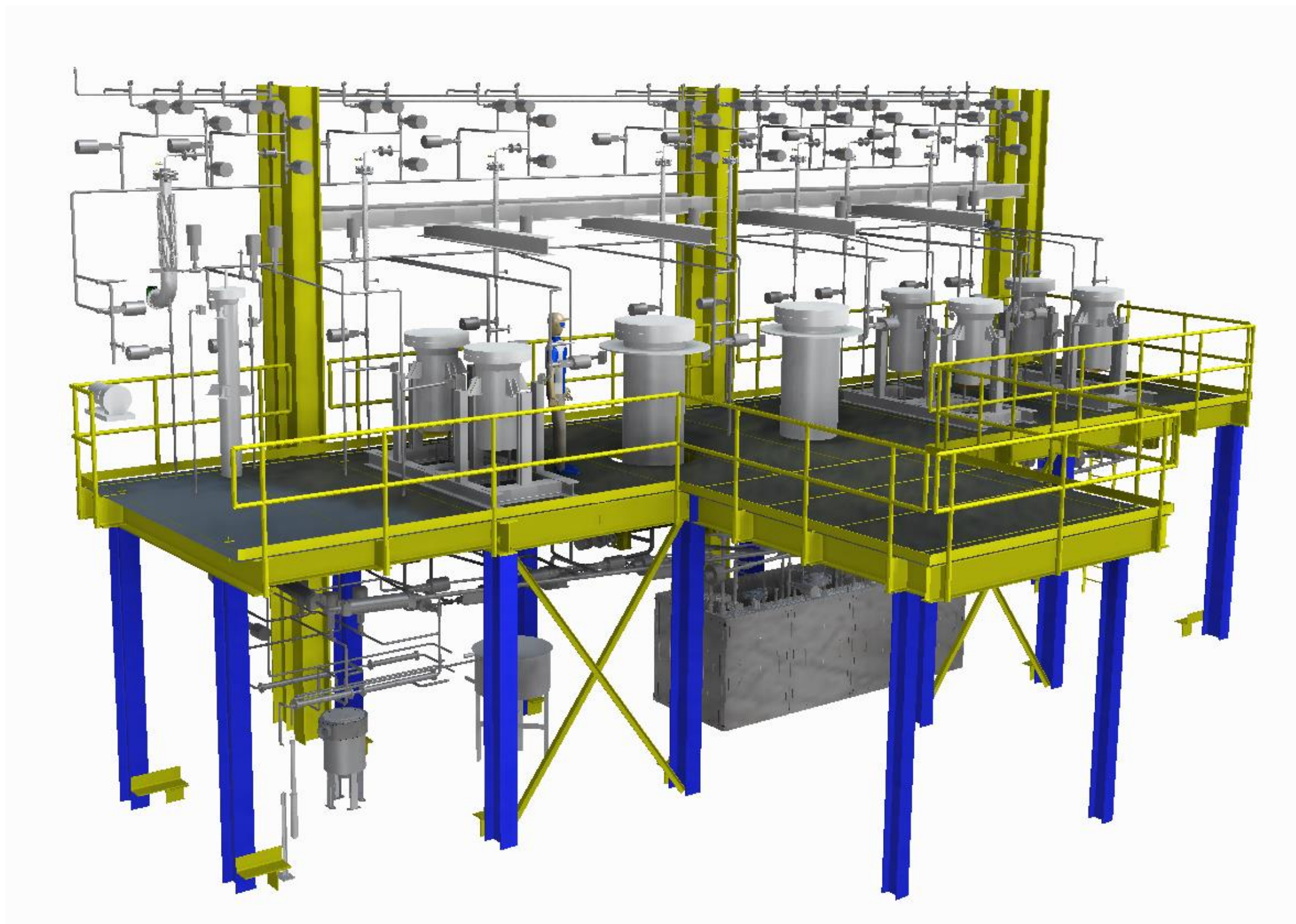
Figure 1 –A 3D model of the Mechanisms Engineering Test Loop showing Phase I and four additional test vessels.

1.2 Phase I Status Overview

Due to the anticipated cost of the entire facility and the expected flow of funding, it was decided to construct METL in phases. Three-dimensional (3D) models of Phase I can be found below in Figure 2 and Figure 3. The following list provides a brief summary of the status for the Phase I systems and components as of August 2018:

Mezzanine & Catch Pan – The mezzanine structure and catch pan are complete. The mezzanine is used to support the vessels and piping system above the dump tank. The catch pan ensures potential sodium leaks do not interact with the concrete floor. (there was no change in FY2018)

Piping System Design – The detailed design and analysis for the METL piping system was completed in late 2015. The plumbing design meets the requirements of ASME B31.3-2012 for Category M fluid service. (there was no change in FY2018)

Piping System Fabrication and Installation - Argonne Central Shops (ANL-CS) coordinated the fabrication, installation, and testing of the METL piping sub-assemblies, supports and system integration. Valves, piping, tubing, fittings, hangers, supports and other required hardware for Phase I are installed. Additionally, ANL-CS machined all piping subassemblies and installed the finished sections into the Bldg. 308 high bay. Welding was performed both on site by ANL-CS and through a local welding and weld inspection company. (there was no change in FY2018)

Heaters & Thermal Insulation – All 272 mineral insulated (MI) cable heaters have been secured to the METL piping system. Ceramic band heaters are mounted on the outer walls of the dump and expansion tank, test vessels, cold trap, and plugging meter. The insulating of Phase 1 has been completed as well. The piping was insulated using 1" of Cerablanket beneath 2" of Pyrogel XT-E. The Cerablanket is installed underneath the Pyrogel to protect the Pyrogel from excessive heat due to the temperature limitations of this insulation material. The valves and vessels have similar insulation construction but the materials are housed in a removable jacket to provide a means of easy access to internal components for troubleshooting and repair. In FY2018, adjustments were made to the heaters of the Swagelok valves, test vessel heaters, and vapor trap heaters as discussed below.

Thermal Mixing Tees – Both of the thermal mixing tees are complete. They are installed downstream of the cold trap and plugging meter to minimize thermal cycling and fatigue in the piping system where sodium fluid streams at different temperatures are mixed. (there was no change in FY2018)

Kammer Valves – Twelve 1.5" pipe Kammer/Flowserve valves have been welded into the METL loop. (there was no change in FY2018)

Swagelok Valves – All Swagelok valves for Phase I have been installed. This includes fifty-two electro-pneumatic and thirty-eight manual valves. Additional valves for future phases are either on-site or installed. In FY2018, it was found that some of the pneumatically actuated valves were not traveling fully. These valves were cycled by increasing the pneumatic valve actuating pressure. In addition, adjustments were made to the heaters as noted below.

Pressure Relief Valves – Fourteen "Toter" pressure relief valves (PRVs) are installed into the vapor space of METL. These PRVs have a set-point of 20 [psig] and are capable of operating at 1200 [°F]. (there was no change in FY2018)

Dump Tank – The 850 [gal] dump tank was shipped to Northland Stainless in order to have the nozzles reinforced. The nozzle loads were calculated using CAESAR-II, an industry standard software package for piping analysis. Post-manufacturing, the calculated nozzle loads exceeded the load allowed for the existing dump tank. Therefore, the dump tank was shipped to the original manufacturer for nozzle reinforcement. The dump tank has reinforced nozzles to withstand the forces attributed to thermal expansion and is installed into the piping system. Lastly, the thermocouples have been tack-welded into position, ceramic band heaters were installed, and its retainer filled with insulation. The dump tank was filled with 750 gallons of reactor grade sodium in FY2018.

Expansion Tank – The expansion tank was also shipped to Northland Stainless to weld on stronger nozzles. The expansion tank had its nozzles reinforced and is installed in METL as well. Expansion tank thermocouples have been tack-welded in place, its ceramic band heaters are installed and covered with insulation jackets. (there was no change in FY2018)

Cold Trap – The cold trap nozzles were reinforced by an outside vendor. The cold trap has been repaired, re-certified, returned to Argonne, and is installed into the METL piping system. The cold trap has its' thermocouples, heaters and insulation jackets installed. Additionally, the blower, variable frequency drive and ducting to remove heat from the cold trap has been installed and tested.

Economizer – The vendor completed and delivered the economizer. The economizer is installed between the cold trap and the main loop as a sodium-to-sodium heat exchanger. At a nominal flow rate of ~ 1[gpm] through the cold trap, the economizer is expected to transfer about 25-30 [kW] when the loop is operating at 1000 [°F]. The economizer has been installed into the METL piping system and is equipped with thermocouples and MI cable heaters. The economizer container has been filled with vermiculite to act as an insulator. In FY2018, additional insulation was added around the economizer to ensure it was touch safe.

Plugging Meter – The plugging meter and its' respective equipment (thermocouples, ceramic band heaters, MI cable heaters, ambient air blower, air duct, and variable frequency drive) have been installed and tested. The plugging meter is also equipped with a removable insulation jacket. (there was no change in FY2018)

Test Vessels – A bid package for new test vessels was sent to several manufacturers. In May 2015, Northland Stainless was awarded the contract to fabricate the two 18" vessels and two

28" vessels for the Phase I of METL. Northland Stainless is the manufacturer of the dump tank and the expansion tank. The two 18" vessels required additional nozzle bracing as well. All of the test vessels were delivered to Argonne in May 2016 and have been installed into METL. The heaters, thermocouples and insulation for all of the test vessels for Phase I of METL are also installed. In FY2018, an attempt was made to heat up the test vessels to their maximum operating temperature. The initial attempt on resulted in obtaining a temperature of ~200C.

Vessel Supports - Central Shops fabricated and installed all of the Phase I vessel supports. The supports for the test vessels and the expansion tank were designed by Argonne engineers to withstand a simultaneous fire and earthquake (850 [°F] / lateral 0.384 [g]). In FY2018, a new test vessel support leg was designed to provide for a thermal standoff between the vessel lug and the support leg to reduce the amount of heat being conducted from the test vessels and to also reduce the temperature of the support legs. Two new test vessel support legs were designed and fabricated. These new vessel support legs are being tested on the test vessel in August and September 2018.

Inert Gas System – A 1000 [L] Airgas micro-bulk system was installed outside the Bldg. 308 high bay. The argon gas supplied by this system will be used to inert the gas space above the sodium and actuate the electro-pneumatic valves. The inert gas system has been connected to METL, fifty-two electro-pneumatic valves, and four mass flow controllers.

Vapor Traps & Filters – The filters and vapor traps for METL have been fabricated by ANL-CS. The dump tank vapor trap was fabricated by an outside vendor. The filters are located downstream of the vapor traps and are the final sodium aerosol filters before the inert gas stream exits the building. All six vapor traps and filters are installed into the downstream system of METL. The vapor traps are equipped with heaters to ensure it remains above the melting point of sodium. During FY2018, the vapor trap heaters for the test vessels and expansion tank were changed out from cable heaters to ceramic band heaters to increase the robustness of the heaters.

Pumps & Flowmeters – All of the electromagnetic pumps and flowmeters have been fabricated, calibrated, and delivered to Argonne. An annular linear induction pump (ALIP) is used to circulate the sodium through the main loop at approximately 10 [gpm]. Two AC conduction pumps are used to push sodium through the cold trap and plugging meter loops. The control panels for the pumps and flowmeters are installed on the METL mezzanine outside of the control room. All of the electromagnetic pumps and flowmeters are installed and wired.

Data Acquisition & Control System – Eurotherm control cabinets were designed to control the heaters and automatic valves on METL. Eurotherm control cabinets have been delivered to Argonne and are installed. An operator can adjust the Eurotherm output by using either a touch-screen interface or a LabVIEW program that communicates to the Eurotherm via Ethernet. All of the National Instruments data acquisition enclosures have been fabricated by Argonne engineers. All National Instruments enclosures are mounted and wired. Additionally, all of the thermocouple umbilical enclosures have been installed and routed.

Carbonation Process – A sodium removal system has been designed and fabricated by Argonne. The system will operate by flowing moist carbon dioxide into a spare test vessel that

contains test articles removed from METL. The carbonation process will then gently react with the unwanted sodium residue to create sodium bicarbonate. The carbonation process underwent commissioning activities to ensure that the system could provide moist CO_2 to the reaction vessel.

Sodium – ≈1000 [gal] of sodium has been delivered from MSSA in (19) 55-gallon drums. 15 (of the 19) 55-gallon drums of sodium were transferred from the drum into the METL dump tank in preparation of METL sodium fill. This transferred occurred without incident at about one drum per day.

Flexi-Cask System – A "Flexi-Cask" system has been fabricated by a local vendor to allow for the insertion and removal of test assemblies from METL test vessels to restrict the atmosphere from entering the vessels. This system is designed to use the crane in the Bldg. 308 high bay and will provide an inert environment that operators can use to handle experiments. Preliminary flexi-cask testing has been performed to understand if the design is performing as intended and whether design modifications need to be made prior to designing and fabricating a flexi-cask system for the 28 inch vessels.

Bldg. 308 Maintenance – A new waterproof membrane was installed on top of the Bldg. 308 hi-bay. Additionally, the exterior of the Bldg. 308 hi-bay was given a new coat of weather-proof epoxy. No changes to B308 were performed in FY2018.

Commissioning of METL – As discussed above, the METL facility dump tank was filled with 750 gallons of sodium in April 2018 and then the facility was allowed to go cold to continue with the commissioning and pre-check activities. The commissioning activities and pre-check activities continued during the Spring and Summer of 2018. During the week of September 3rd and 10th, the METL system was reheated in preparation for the filling of the main loop, purification and diagnostic systems, and the expansion tank. On September 19, 2018, at approximately 1400, sodium was transferred from the dump tank through the fill line into the main loop using an argon push. The sodium was then pulled through the purification and diagnostic systems into the expansion tank. The overall fill process took about 5 minutes. Sodium flow was established in the purification system by turning on the cold trap conduction pump. Sodium flow was registered on the cold trap flowmeter. The sodium in METL will undergo purification and commissioning activities will continue for about three weeks into October.

1.3 Acknowledgement

coordinated efforts of William Toter and Robert Sommers of Argonne's Central Shops. In addition, we gratefully acknowledge the outstanding welding capabilities of Damon Simpson, Robert Sommers, and Daniel Berkland; whose welds passed radiography and dye penetrant testing every time.
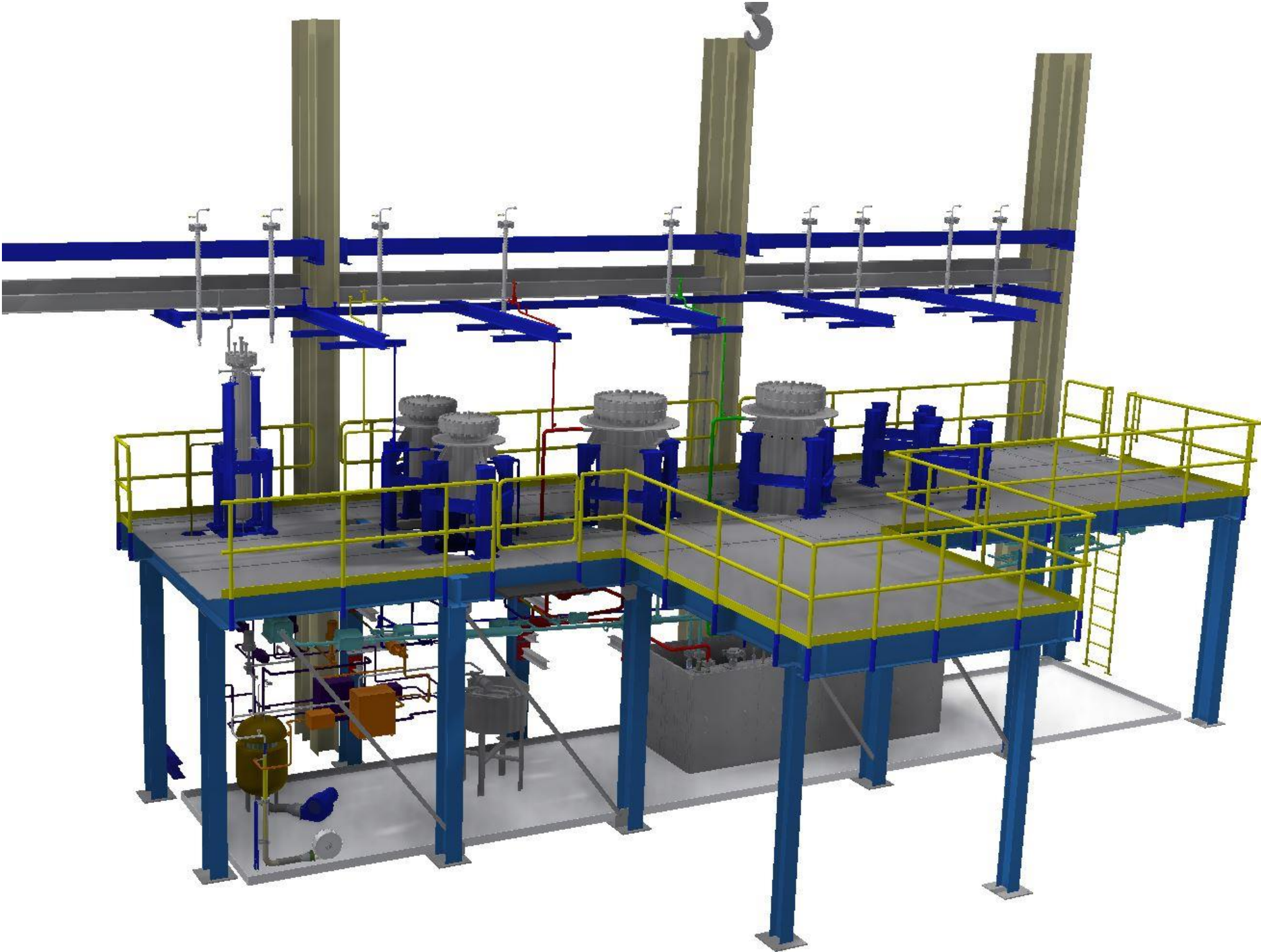
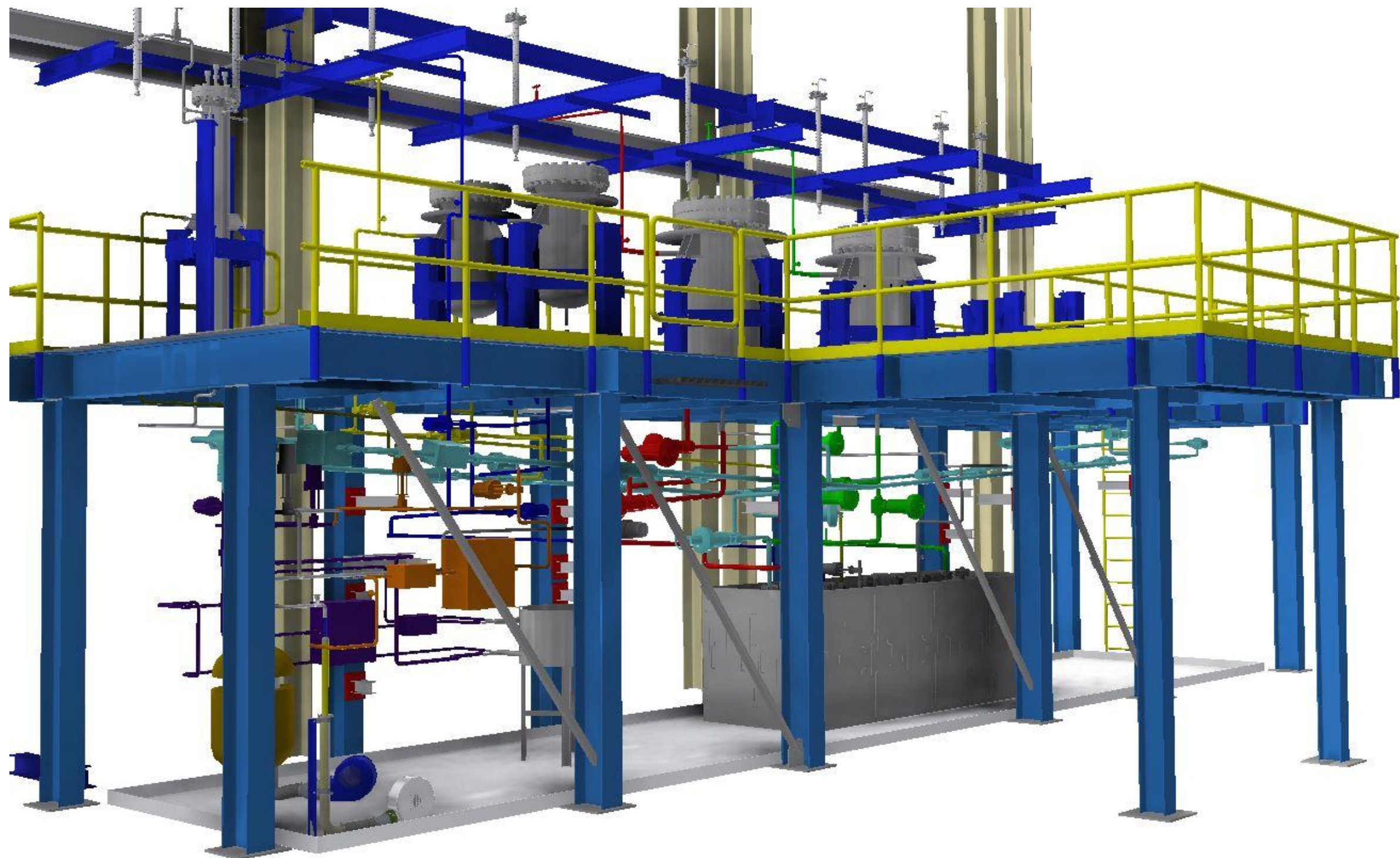*Figure 2 – A 3D model of METL after Phase I is complete.*

Figure 3 - A 3D model showing the Phase I piping and equipment arrangement underneath the mezzanine.

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2   Background and Objectives

The successful operation of sodium-cooled fast reactors will largely depend on how well all of the components work within a sodium environment. Therefore, the mission of the Mechanisms Engineering Test Loop (METL) is to provide the infrastructure and technical expertise required to test advanced technologies in a high-temperature sodium environment. In turn, the results gleaned from experiments performed in METL will help to develop state-of-the-art advanced reactors.

2.1 Design Overview

The layout of METL follows the characteristic design of a sodium test facility. The facility consists of multiple test loops in which tanks/vessels, valves, and other components are interconnected via piping and tubing. The system is designed to handle both static and flowing sodium which permits each test vessel to be configured to suit the particular needs of an experiment. During operation, the sodium is purified by passing it through the cold trap. Impurity levels can be continuously monitored using the plugging meter. The general design temperature of the facility is 1000 [°F] but the maximum design temperature of the 28" test vessels is 1,200 [°F].

3 System Description & Status

3.1 METL Phase I Design

Fabrication of Phase I for the METL facility was focused on the main sodium loop, dump tank, two large (28") test vessels, two intermediate (18") test vessels, the purification system, the heating and control system, the expansion tank, and the mezzanine. Future phases will incorporate other components (e.g., a heat exchanger), test facilities, or install additional test vessels.

All piping, test vessels, and tanks are equipped with heaters and insulation that can maintain sodium temperatures ranging from room temperature to a minimum of 1000 [°F]. The large 28" vessels are designed to contain static sodium up to 1200 [°F]. The temperature for each individual vessel, tank, or component can be adjusted by PID-controlled heaters to suit the particular needs of a test.

The density of sodium changes from ~920 [kg/m³] to ~825 [kg/m³] when heated from 208 [°F] to 1000 [°F]. The additional volume (about an 11.5% expansion) can be compensated for by using either the expansion tank or the cover gas space within each test vessel.

As shown in Figure 4, each test vessel has dedicated lines for sodium supply, return, overflow, and drain. Additionally, all test vessels are connected to an argon supply line and a vent line that is connected to a vapor trap. With only one vessel on-line, the maximum flowrate through a vessel will be 10 [gpm]. The sodium overflow line is used to control the sodium levels in the test vessels. A sodium dump can be carried out independently for each test vessel by opening the associated dump valve in case of an emergency.

The large catch pan (~1000 [gal]) located under the mezzanine is designed to collect METL sodium spillage in the event of a sodium leak. The catch pan maintains a barrier between the spilled sodium and the underlying concrete.
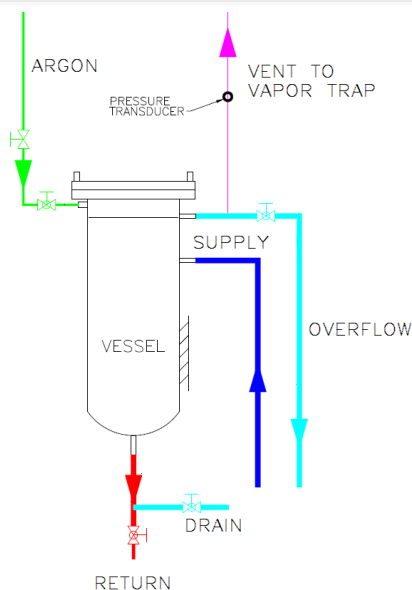
Figure 4 - A depiction of the various test vessel connections and their orientation.

3.2 Status of Phase-I Subsystems & Components

3.2.1   *Mezzanine & Catch Pan*

The test vessels are be installed on top of a mezzanine structure so they can be located above the main piping system, dump tank, and catch pan. METL was designed this way so that the elevation difference between the test vessels and dump tank would assist with draining in the event of an emergency, such as a leak.

The mezzanine structure was designed by Argonne engineers before it was sent to an architecture/structural engineering firm for final analysis. The structure is meant to support six separate 12,500 [lbs] vessels that are evenly-spaced and centered on the mezzanine. The design loads were conservatively estimated to allow for future expansion of the facility by adding additional tanks or other experimental equipment. Figure 5 shows an overhead photo of the completed mezzanine before the vessel supports or deck plate penetrations were added.

Figure 5 – A photo taken from above the mezzanine looking West to East. This photo was taken before vessel supports or deck plate penetrations were added.

The completed catch pan is installed beneath the mezzanine structure, as shown in Figure 6. The catch pan is made from 3/8" thick ASTM 516 Grade 70 plate and was designed to hold the entire sodium inventory of METL in the event of a leak. The catch pan features all-welded construction to ensure that sodium does not interact with the concrete floor. The catch pan is not directly anchored to the ground, but is instead held in a flat position using a series of large tabs, as shown in Figure 7, mounted to the mezzanine columns. These tabs allow the catch pan to thermally expand and accommodate a sudden high-temperature sodium leak.

Figure 6 – A photo of the catch pan under the METL mezzanine. The catch pan can hold ~1000 [gal] of sodium and is made from 3/8" plate. (Areas where paint has been removed were subjected to weld analysis.)

Figure 7 – Photos of the tabs used to position and flatten the catch pan. Left - a tab connected to the mezzanine structure. Right - a tab anchored to the floor that is used to hold flat the catch pan.

3.2.2   *Piping System*

3.2.2.1 Piping Design

A vendor was contracted to design the METL piping system in February 2014. Argonne received the final package of deliverables from the vendor in May and June 2015. Their scope of work was completed and the contract was closed out in February of 2016. According to their scope of work, the vendor was responsible for:

a) Designing the entire METL piping system (not just Phase I) to meet Argonne technical requirements and ASME B31.3-2012 for Category M fluid service.

b) Developing the piping and valve support systems.

c) Creation of all drawings required for a fabricator to build the piping system.

The current piping configuration is reflected in Figures 1, 2, and 3. The latest piping and instrumentation diagram (P&ID) for METL can be seen in Figure 8. 3D models of the Phase I piping system below the mezzanine can be seen in Figure 9 and Figure 10. The piping design documentation was accepted in September 2015.
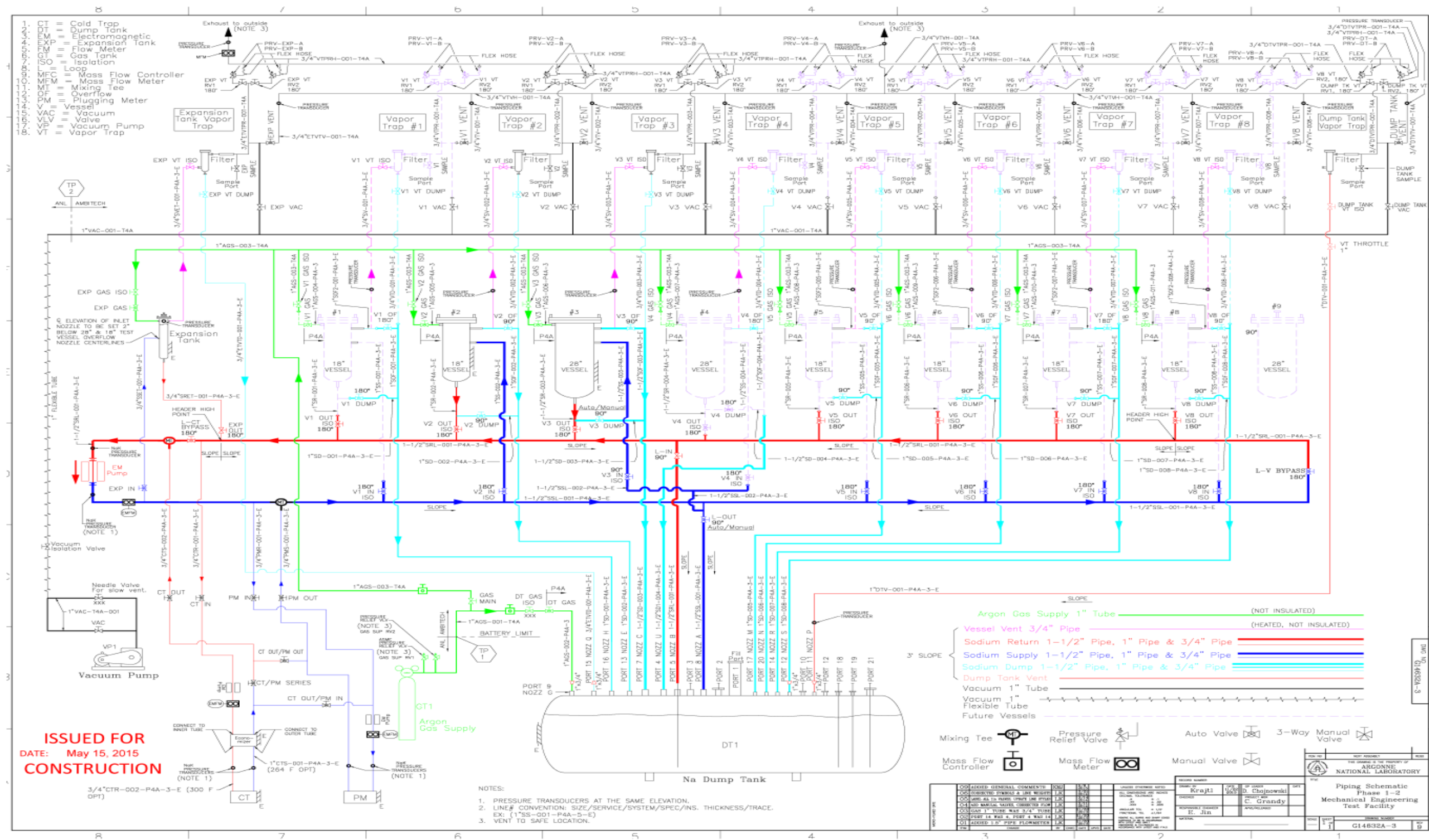
Figure 8 - The METL P&ID that was issued for construction by Ambitech (13).
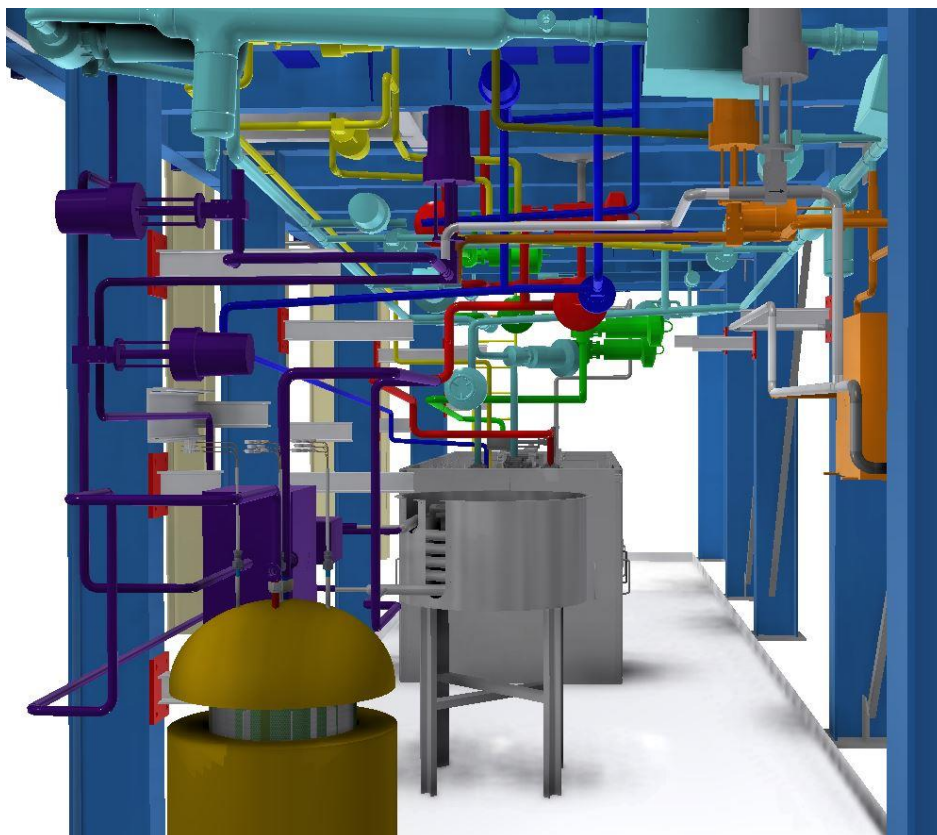
*Figure 9 - A 3D model of the uninsulated Phase I piping system beneath the mezzanine.
(View faces east.)*

*Figure 10 - A 3D model of the uninsulated Phase I piping system beneath the mezzanine.
(View faces west).*

3.2.2.2 Piping & Hardware

All of the piping, pipe fittings, and hangers/supports required for Phase I have been delivered to Argonne and hardware for Phase I is installed. The METL piping system is constructed from seamless 316/316L piping and tubing.

The seamless 316/316L piping, shown in Figure 11, was delivered by a vendor in 10 [ft] lengths. All piping was produced in the US and meets the requirements of ASTM A312. Extra piping and fittings were purchased to have spare material on-hand during fabrication and to allow for weld qualification on the actual materials that will be installed.

Table 1 – Delivered piping for Phase I METL

Pipe Size (Sch. 40)	Qty. [ft]
0.75"	520
1"	520
1.5"	270
Total	**1310**

Over six hundred (634 total) pipe fittings were ordered. All seamless 316/316L fittings were produced in the US and meet the requirements of ASME B16.9 and ASTM A403 WP-S. As shown in Figure 12, the piping and fittings were machined with a custom 'J'-groove in preparation for the automatic welding procedure. Prior to welding, all piping and fittings were cleaned using custom tanks filled with Citranox, as shown in Figure 13.

All 78 of the custom-engineered 'spring can' supports (Figure 14) for the final phase of METL were delivered. Figure 15 through 18 demonstrate different types of hangers and supports that were used to support the METL piping system. All support hardware was connected to the piping using lugs or shoes, which are depicted in Figure 16 and Figure 17

Figure 11 - A photo of the seamless 316/316L piping delivered to ANL Central Shops. Piping was ordered in 10 [ft] lengths from Northern Illinois Steel. All piping is 1.5", 1", or 0.75" Sch. 40.

Figure 12 - A photo of the pipe fittings that were prepped for welding.
(Left = as received, Right = with 'J' prep.)

Figure 13 - A photo of METL piping components being washed in a Citranox bath.

Figure 14 - A photo of the METL piping hangers and support.

Figure 15 – Picture of the piping supports. The spring can hangers are welded to the support steel underneath the mezzanine.

Figure 16 - A photo of a pipe lug that is connected to the spring can.

Figure 17 - A picture of a pipe shoe that is supporting a section of the piping from underneath.
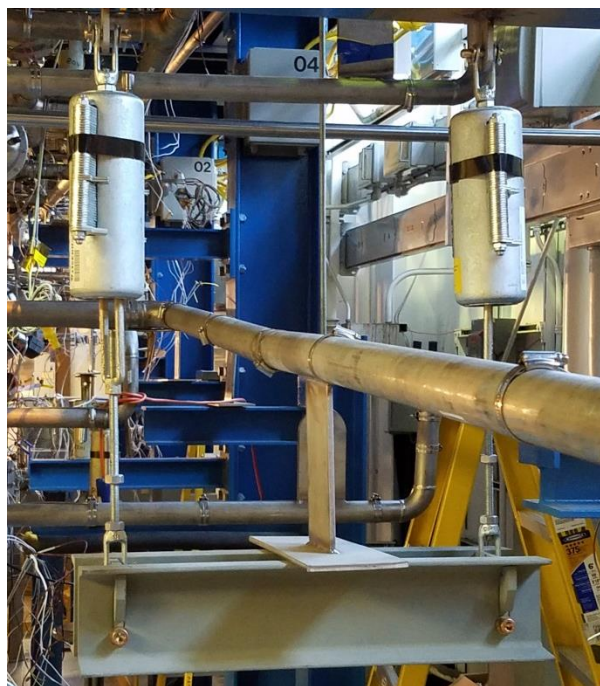
Figure 18 – A section of the METL piping being supported by a trapeze via spring cans.

3.2.2.3 Pipe Fabrication & Installation

ANL-CS has completed the installation of the pipe hanger support steel located below the mezzanine, as shown in Figure 19. Additionally, ANL-CS has finished the fabrication of the

horizontal support steel and pedestal supports for the piping system and/or equipment, shown in Figure 20.

Pipe and pipe fittings were machined by ANL-CS according to the piping isometric drawings, depicted in Figure 21. Pipe subassemblies were welded by both ANL-CS and a local vendor. Any piping weld that is expected to be exposed to liquid sodium underwent radiographic non-destructive examination, which exceeds the 20% inspection requirement according to ASME B31.3 piping code requirements for Class M fluids. Examination of the welds was performed onsite by a vendor and off site at another vendor's quality control facility. Additionally, Argonne Quality Assurance (QA) inspected all of the field welds utilizing dye penetrant. All of the welds have passed radiography and dye penetrant testing. The results of the qualified welding procedure are shown in Figure 22. The piping fabrication and installation was completed in October 2016.

Figure 19 - A photo of the pipe hanger support steel located beneath the mezzanine. All supports are A36 L4"x4"x3/8" angles connected to the mezzanine using welded tabs and ½"-13 fasteners. (Note: all welds were repainted before piping assemblies are installed.)

Figure 20 - A photo of the horizontal piping supports prior to installation. These supports were bolted to the vertical columns beneath the mezzanine.

Figure 21 - A sample piping ISO produced by ANL. This updated ISO is based on Ambitech drawings but gives Central Shops the required dimensions of the piping and equipment prior to installation.

Figure 22 - A photo of sample welds on 0.75" and 1" piping. The initial automatic weld and the subsequent manual TIG weld can be seen for both pipe sizes.

3.2.2.4 Pipe to Tube Transitions and Reinforcements

Tubes and pipes were used to construct the METL piping system as they are readily available in stainless steel and are both suitible for sodium service. However, the sizing designation between tube and pipe is quite different. Tubing size is specified by an outside diameter and wall thickness (e.g. 1" - 065 tube is a piece of tubing with a 1" outside diameter and a 0.065" wall thickness). Piping is specified by schedule and pipe size but is less intuitive than tubing (e.g. 1" schedule 40 pipe has an outside diameter of 1.315" and a wall thickness of 0.133").

The fact that 1 inch tubing and 1 inch pipe have different dimensions led to the creation of pipe to tube transitions (Figure 23). Due to stress caused by different operating conditions of METL, a few sections of pipe to tube transitions required extra material welded on as a reinforcement. These reinforcements ensured the transitions would be able to withstand the thermal expansion stress. An example of a transition reinforcement is presented below in Figure 24.
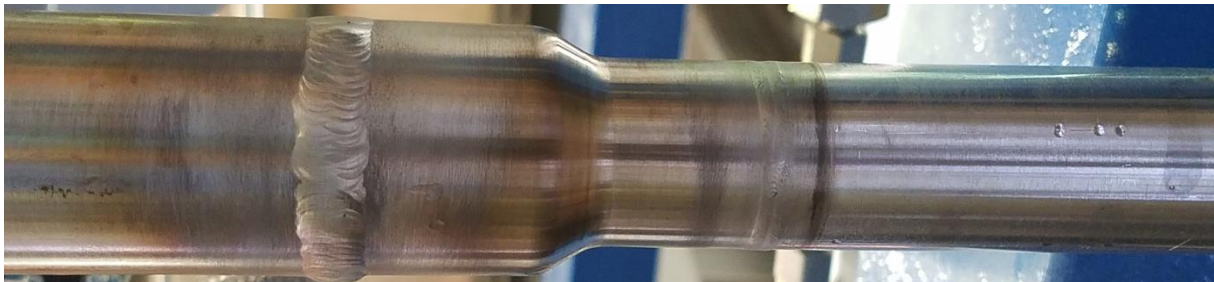
Figure 23 – A 1in pipe to 1in tube transition.
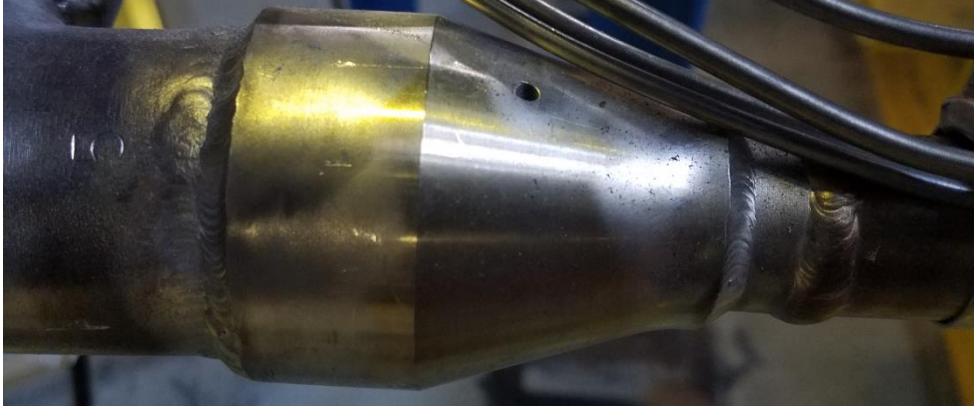
Figure 24 – Reinforced pipe to tube transition.

3.2.2.5 Heaters & Heater Zones

The METL piping system is heated using mineral insulated (MI) cable heaters. These long, flexible heaters are formed and banded onto the piping system to create "heater zones" of different lengths and geometries (Figure 27).

During FY2014, Argonne engineers talked to mineral insulated (MI) cable heater manufacturers to discuss the METL trace heating design. Conversations with vendors indicated that a linear power density of 60 [W/ft] was appropriate for MI cable heaters banded to the outside of 1000 [°F] piping.

As shown in Figure 25, a series of tests were conducted with 1/8" and 1/4" diameter MI cable heaters to determine their suitability for METL. During these tests, the MI cable heaters were attached to a 6' length of empty 1.5" Schedule 40 pipe and then wrapped in ceramic-blanket insulation. The major results from these tests were:

a) Both 1/8" and 1/4" diameter MI cables were able to heat the entire surface of the pipe to at least 1000[°F] within several hours using 60 [W/ft]. (The maximum expected heat/cool rate for METL is ~300 [°F] per hour, as recommended by the manufacturer of Grayloc fittings.)

b) MI cable heaters have an outer diameter of 0.25" or greater to provide adequate electrical insulation (Table 2).

c) The maximum temperature difference around the pipe was measured to be ~75 [°C], as shown in Figure 26.

In FY2015, the piping design was completed by the vendor and Argonne engineers were able to plan the MI cable heater zone layout using the finalized 3D models. Guidance for determining heater zone parameters was provided by the former Manager of the Energy Technology Engineering Center. Using the guidelines to size the heater zones on the sodium-filled pipe, it was determined that Phase I piping requires 136 heater zones. The heater zones and their respective process control thermocouples were determined by adhering to the following rules.

a) Heater zones cannot be longer than 10 [ft].

b) Changes in elevation must be limited to 3 [ft].

c) A pipe heater zone starts/ends whenever there is a vessel, valve, or grayloc fitting.

d) Each valve is an individual heater zone.

e) Heater zones greater than 3 [ft] must have two process control thermocouples which are to be installed in 1/3's of the overall length.

f) Heater zones less than 3 [ft] have one process control thermocouple and is installed at the midpoint of the overall length.

Figure 25 - A photo of the insulated MI cable heater test setup. Thermally insulating fire-bricks were used to keep the piping off the ground. This picture shows the pipe wrapped in ~ 2.5" of Morgan Thermal Ceramic insulation
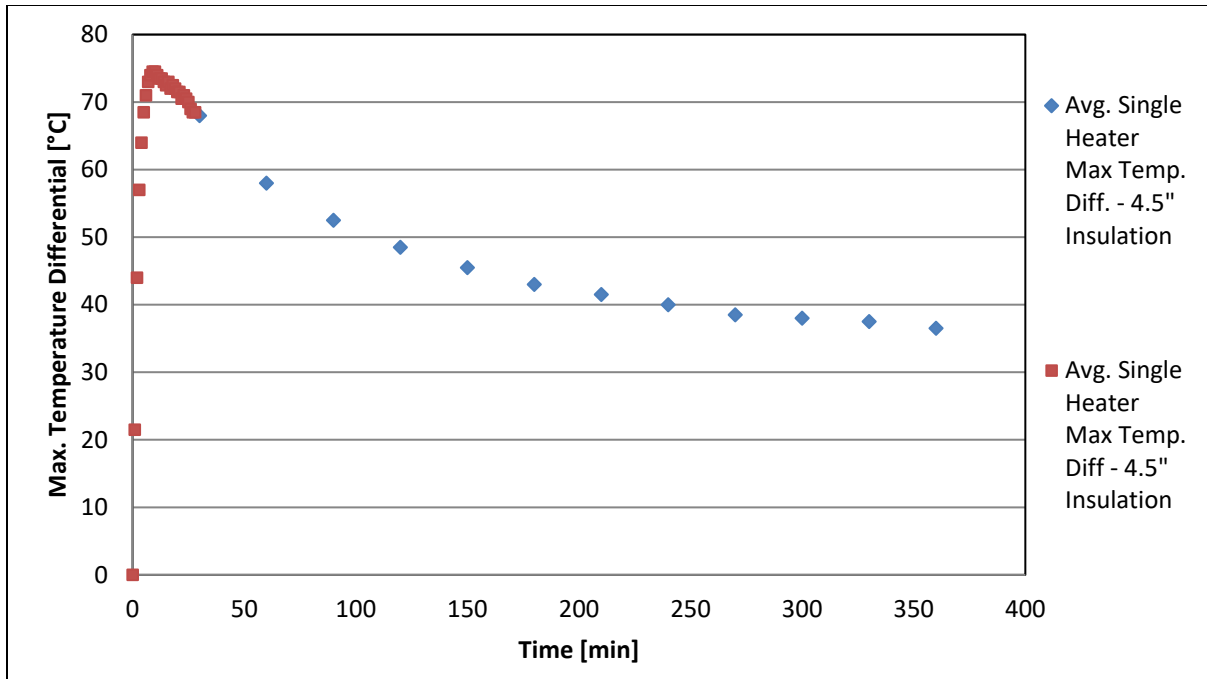
Figure 26 – The maximum measured temperature difference the heated 1.5'' Schedule 40 pipe using a single heater. This temperature differential was achieved by leaving a single heater in the 'on' position.

Table 2 – The results of the heater electrical insulation tests.

	1/8" Diameter	1/4" Diameter
Before Testing	> 0.1 [GΩ] @ 500 [VDC]	> 10 [GΩ] @ 1000 [VDC]
After Testing	21.5 – 24.4 [MΩ] @ 500 [VDC]	1.60 – 1.71 [GΩ] @ 1000 [VDC]

In FY2016, Phase I of the METL piping system was broken into 136 individual heater zones of various lengths. Heater zones less than 18 [in] could not be supplied with 240VAC so two 120VAC cable heaters were installed in their place. Also, each zone has a second MI cable heater for redundancy. Therefore, the METL piping system has 352 MI cable heaters, 352 internal type K monitoring thermocouples, and 229 process control thermocouples. An example of the MI cable heater and process control thermocouple installation is illustrated below in Figure 27.
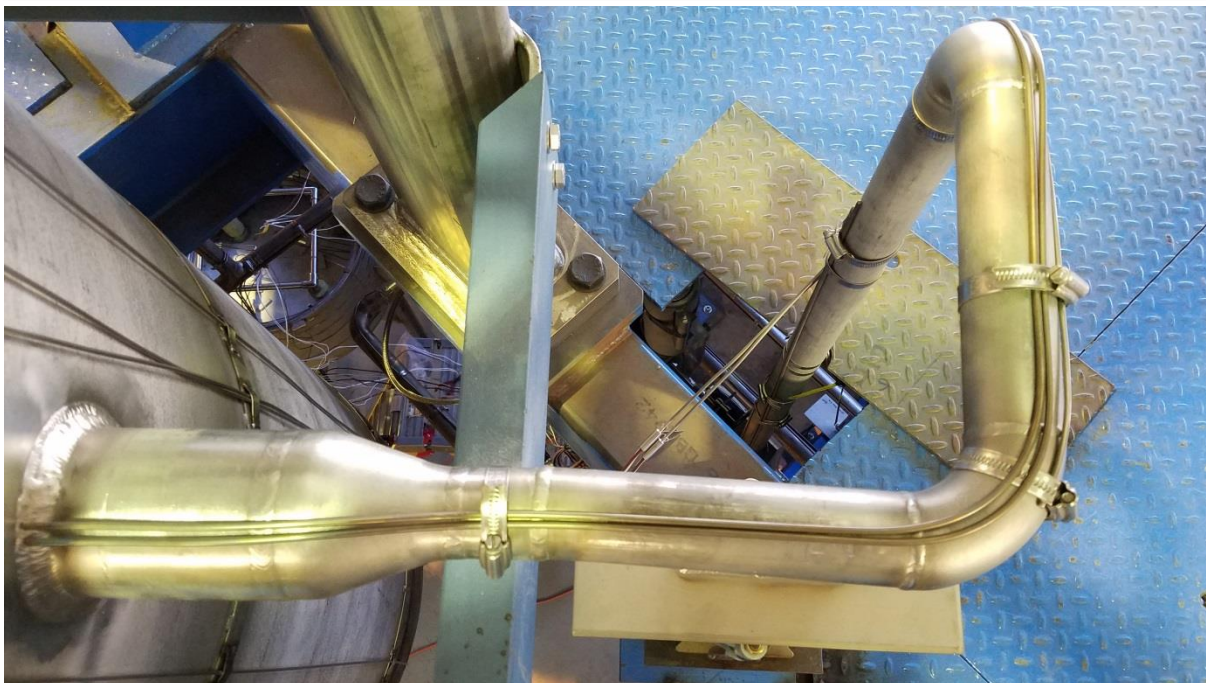
Figure 27 – MI Cable heater and type-K process thermocouple banded onto the outer wall of a segment of the METL plumbing system.

The piping system heater zones first had their process control thermocouples tightly strapped to the piping zone via 316 stainless steel hose clamps. Then the MI cable heaters were lightly strapped to the piping zone utilizing 316 stainless steel hose clamps, following a similar path as the aforementioned thermocouple. This allows for a close contact between the control thermocouple and the pipe as well as increased longevity of the MI cable heater during thermal expansion and contraction. As illustrated in Figure 28, the piping has thermocouples and MI cable heaters strapped to the outer diameter which are surrounded by 1 [in] of cerablanket and 2 [in] of pyrogel insulation.
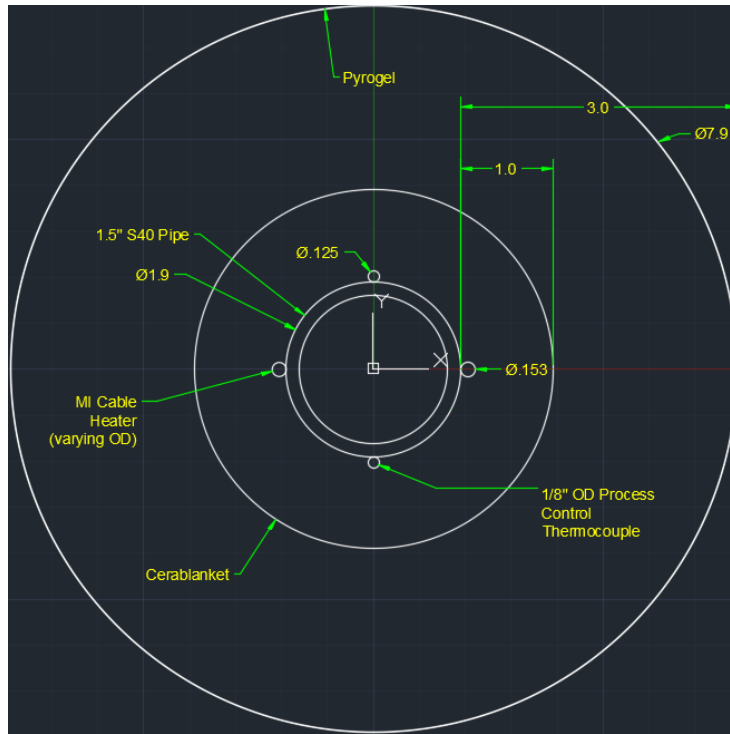
Figure 28 – Pipe Installation with process control thermocouples, MI cable heaters, cerablanket insulation, and pyrogel insulation.

3.2.2.6 Piping Insulation

Argonne engineers have decided to insulate the METL piping system using 1" of Cerablanket beneath 2" of Pyrogel XT-E. (The inner layer of Cerablanket protects the Pyrogel XT-E from the high-temperature MI cable heaters.) As shown in Figure 29 and Figure 30, using advanced insulating materials such as Pyrogel XT-E instead of traditional insulation like mineral wool or calcium silicate (CalSil) allows the METL piping system to achieve identical levels of thermal performance at a fraction of the overall size (diameter) and weight.

The sodium-compatibility of Pyrogel XT-E was investigated during FY2014 when a series of burn tests were performed to evaluate potential hazardous interactions with high-temperature sodium. As shown in Figure 31, bricks of sodium were placed on top of the Pyrogel XT-E within the Bldg. 308 burn stall. For each test, 1 [lb] of sodium was ignited using an oxy-acetylene torch. Each fire was permitted to burn to completion (10-15 [min]) and the burns were recorded on video tape. These tests indicated that Pyrogel XT-E behaved comparably to Cerablanket, which has been used successfully on other sodium systems.

In addition to the sodium burn tests, the Pyrogel XT-E was also studied by the Analytical Chemistry Laboratory (ACL) at Argonne. This investigation confirmed the high-temperature stability of Pyrogel XT-E as well as its chemical and physical composition.

Table 3 shows that the Pyrogel XT-E lost about 7-8% of its mass in going from room temperature to 800 [°C] / 1472 [°F]. (Manufacturer data states that the insulation is only rated to 650 [°C].)

Table 3 – Weight loss data for Pyrogel XT-E at several temperatures as measured by Argonne ACL.
(Samples were held at temperature for at least 4 [hrs].)

Sample	Fraction of Initial Mass After Heating to Temperature, wt%			
	200°C / 392°F	400°C / 752°F	600°C / 1112°F	800°C / 1472°F
Pyrogel XTE #1	97.8	95.6	93.2	92.7
Pyrogel XTE #2	98.0	95.5	92.9	92.4
Average:	97.9	95.5	93.0	92.5
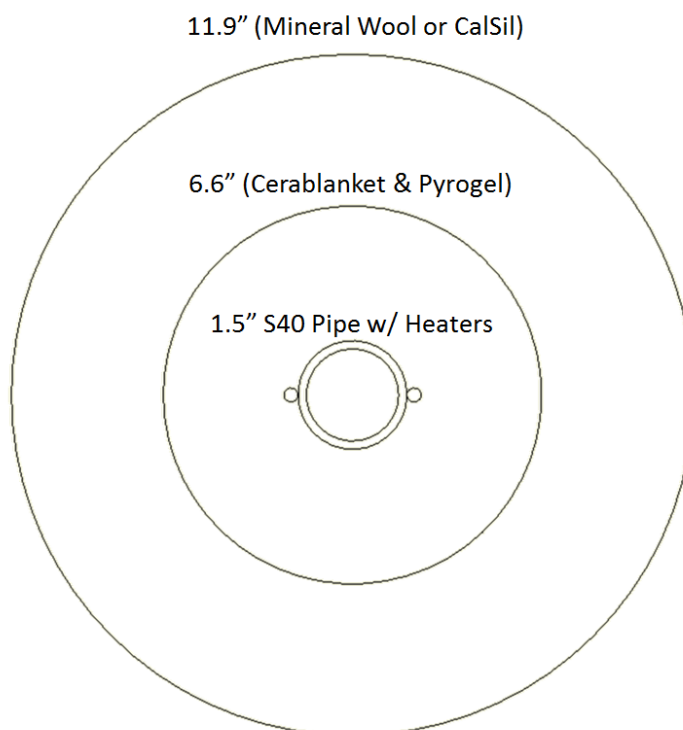
Figure 29 – A comparison of the required insulation thicknesses using different types of insulation. Thicknesses were calculated assuming an operating temperature of 1000 [°F] and a heater power input of 60 [W/ft]. Pyrogel XT-E has a maximum operating temperature of 1200 [°F] so a 1" layer of Cerablanket must be placed between the Pyrogel XT-E and the MI cable heaters.
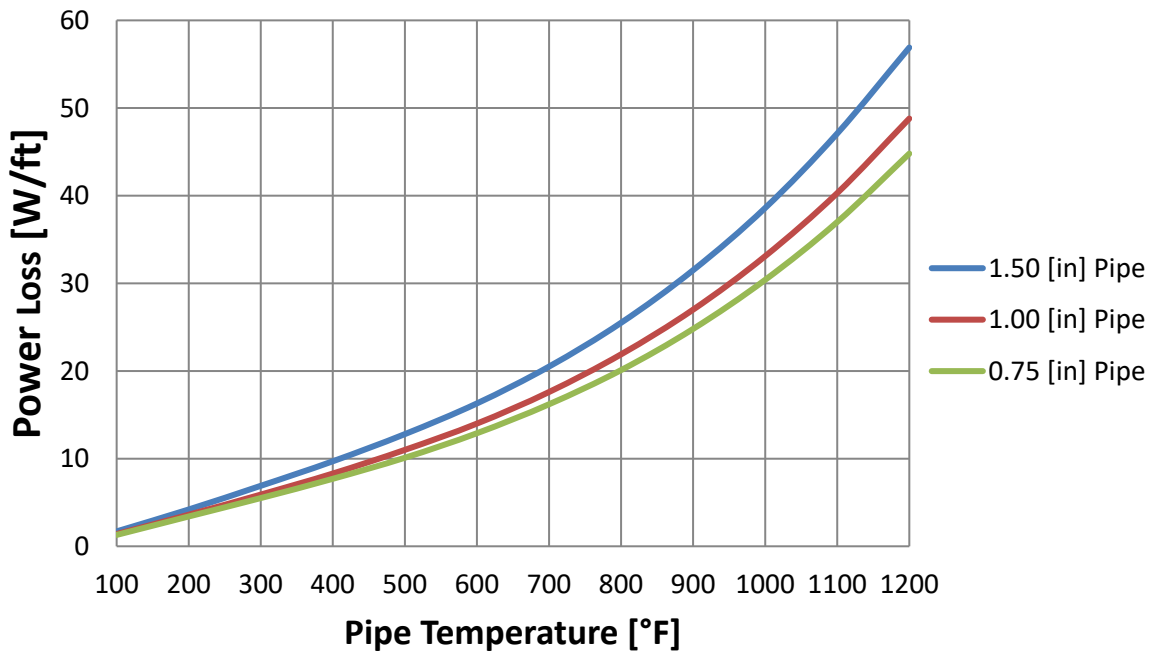
Figure 30 – The predicted METL piping thermal losses using 1" Cerablanket + 2" Pyrogel. The ambient temperature was assumed to be 32 [°F].

Figure 31 – Left: A photo of 1 [lb] of sodium resting on top of Pyrogel XT-E insulation. The insulation was inserted into a steel burn pan and the fires were carried out in the Bldg. 308 burn stall. Right: A still-frame from the video footage of the sodium burns. The flames above the Pyrogel XT-E reached a maximum height of 12-18",
which was comparable to the Cerablanket tests.

Brock Industrial began insulating METL in March of 2017. As described previously, the piping was insulated with Cerablanket (white insulation) and then Pyrogel (pink insulation) as shown in Figure 32 (left). Lastly, the insulation was housed in a thin, stainless steel shroud (Figure 32, right). Brock Industrial has completed all of the insulation for Phase I. The duration of the piping insulation work was about 2-3 months.
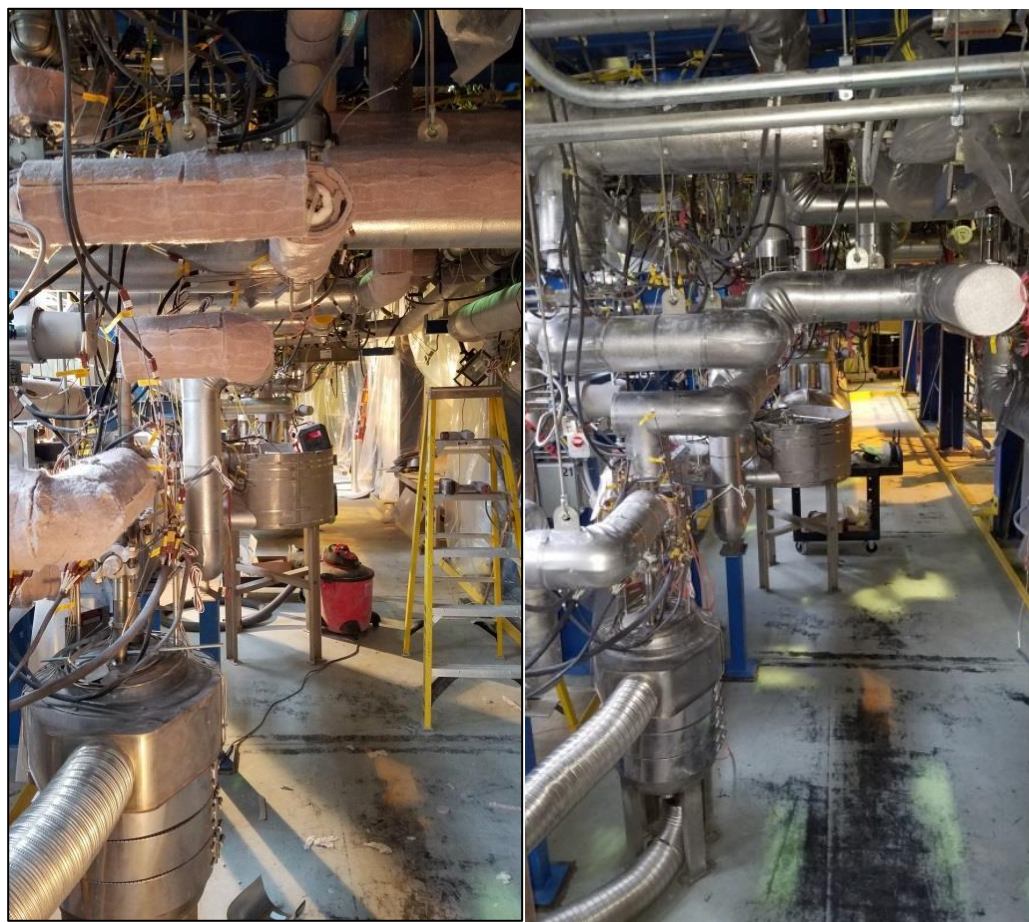
Figure 32 - Piping Insulation

3.2.3   *Valves*

3.2.3.1 Kammer / Flowserve Valves

The main loop of the METL facility uses 1.5" Sch. 40 piping. Valves connected to the main loop must be made from sodium-compatible materials, have a weld-bellows seal to ensure leak-tightness, and be capable of operating at 1200 [°F]. Given these size and technical requirements, Argonne engineers decided to use valves made by Kammer / Flowserve that have the following features:

- Integral Seat
- Seal welded design for reliability
- Thermowell connection
- Angle body bellows cycle life ~ 25,000 full cycles
- Maximum operating conditions: 365 [psig] @ 1000 [°F] / 185 [psig] @ 1200 [°F]
- Electro-pneumatic operation (24 [VDC] control voltage, ~50 [psig] supply pressure)
- Submerged welded bellows design (see Figure 35)

Figure 33 shows a drawing of the straight (180°) valve with actuator and Figure 34 shows the angle (90°) valve with actuator. Kammer valves are used on equipment which has 1-1/2" piping. Currently, this includes the two 28" test vessels, dump tank, and primary sodium loop. There are a total of twelve Kammer valves; five 180° straight valves and seven 90° angle valves. Since, each valve is a unique heater zone; the Kammer valves have two ceramic band heaters strapped to them (Figure 37).

DN/Size: 1 1/2"
PN/Class: 300#
Body mat.: 316 H

Valve Type: 1353P3
Actuator: P3-13

Serial No.	TAG No.

H8211.003-01
H8211.003-02
H8211.003-03

Flowserve Pittsburgh
Order: 5100081242

Customer: ArgonneNatLab/Lemont.IL
PO#: 3E-30141

End Connection
ButtWeld Ends 1 1/2" Schedule 40
3" BW Extensions
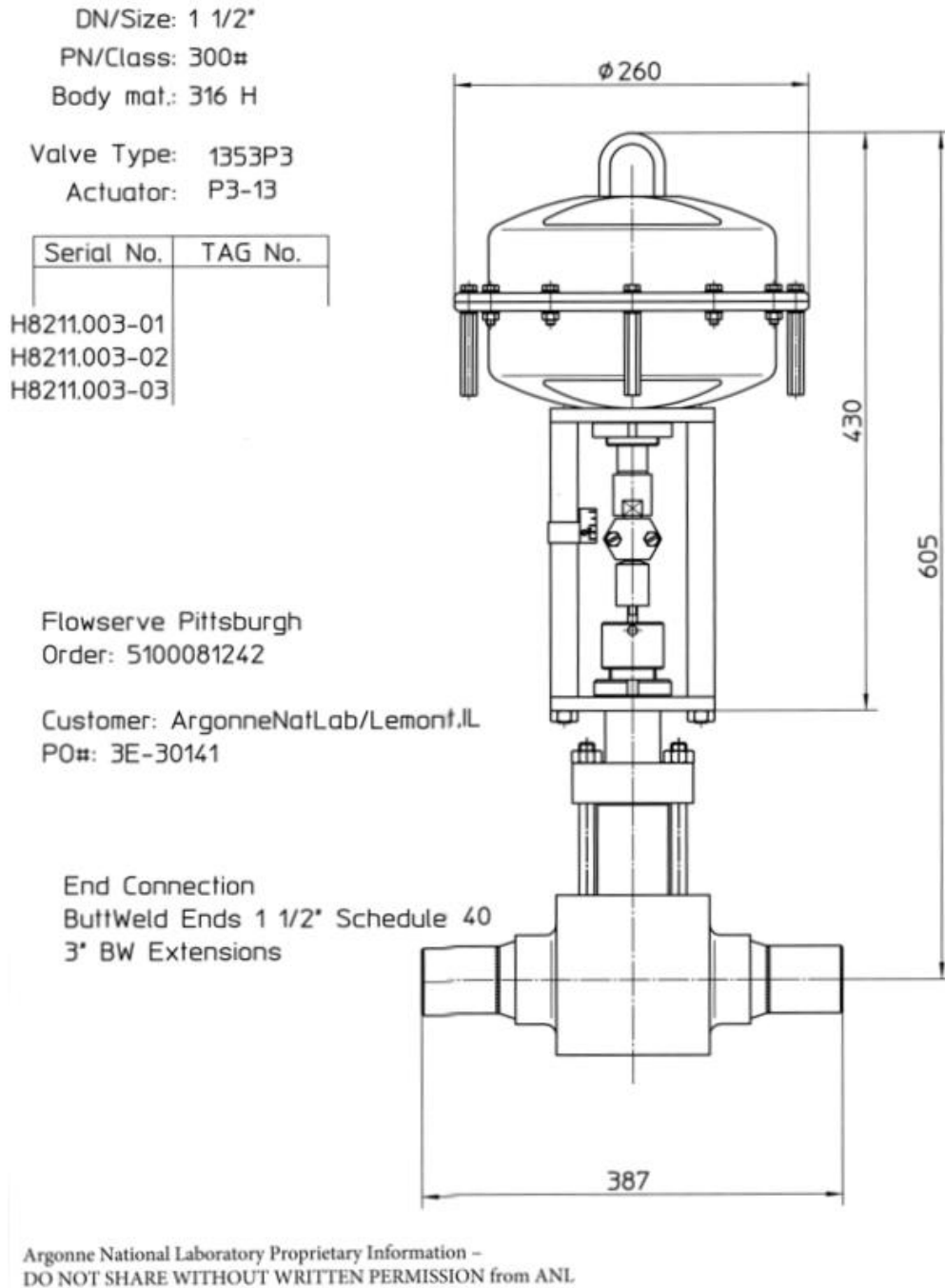
Figure 33 – The cut sheet for the straight Kammer valve (13).

DN/Size: 1 1/2"
PN/Class: 300#
Body mat.: 316 H

Valve Type: 1313P3
    Actuator: P3-13

Serial No.	TAG No.

H8211.001-01
H8211.001-02
H8211.001-03

Flowserve Pittsburgh
Order: 5100081242

Customer: ArgonneNatLab/Lemont.IL
PO#: 3E-30141

End Connection
ButtWeld Ends 1 1/2" Schedule 40
3" BW Extensions

Ø260

430

580

142

142
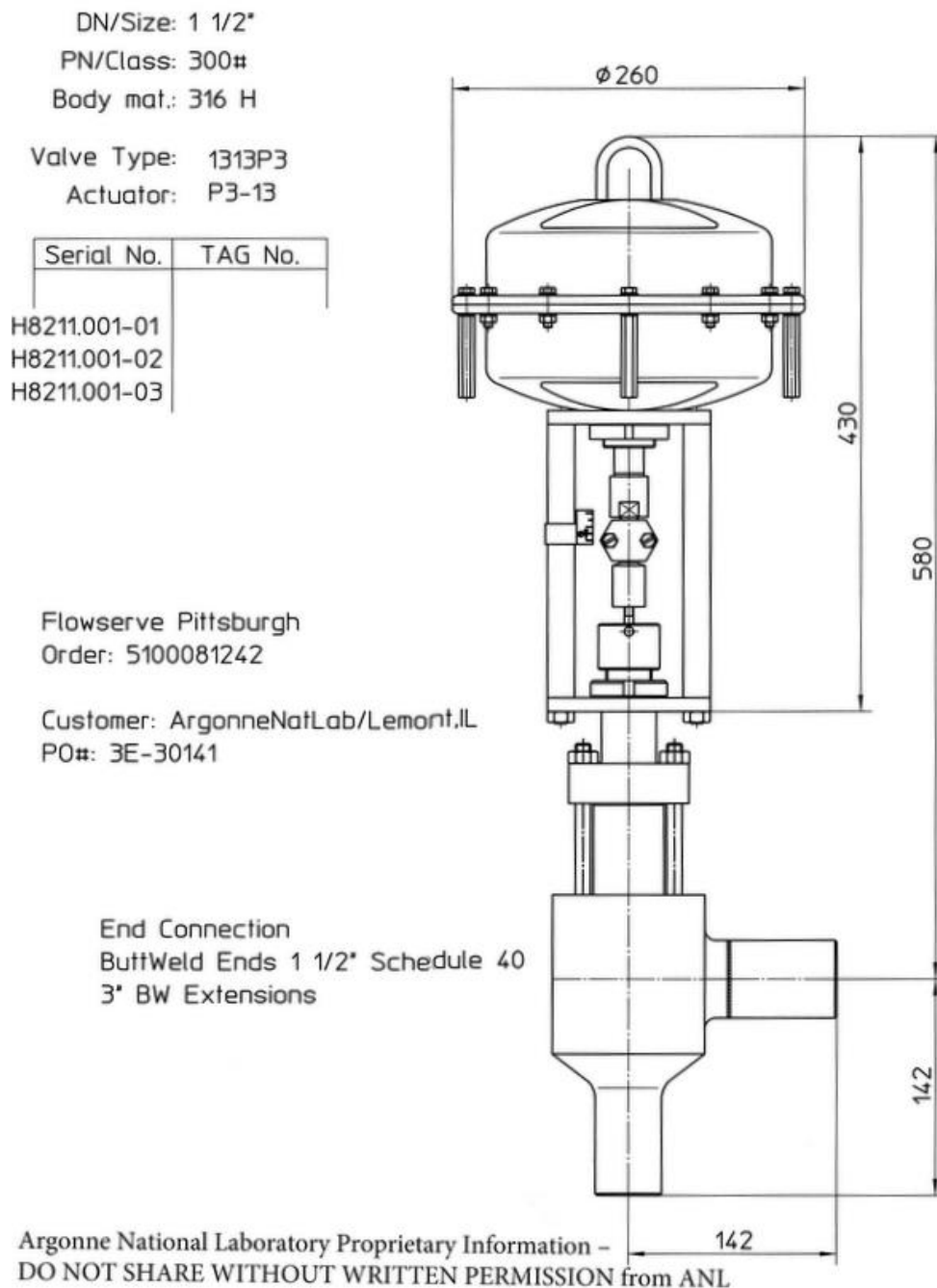
Figure 34 – The cut sheet for the 90° Kammer valve (13).
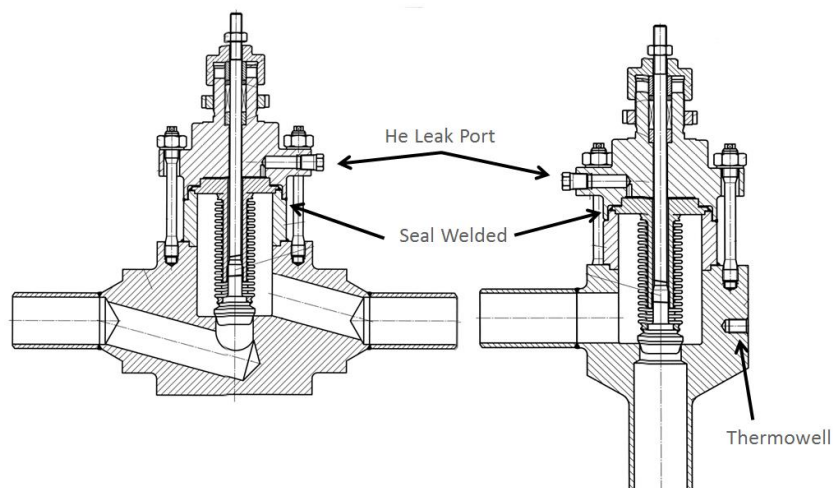
Figure 35 - A depiction of the submerged welded bellows within the Kammer valves. Sodium flowing past the submerged bellows reduces the chances of impurity buildup (13).
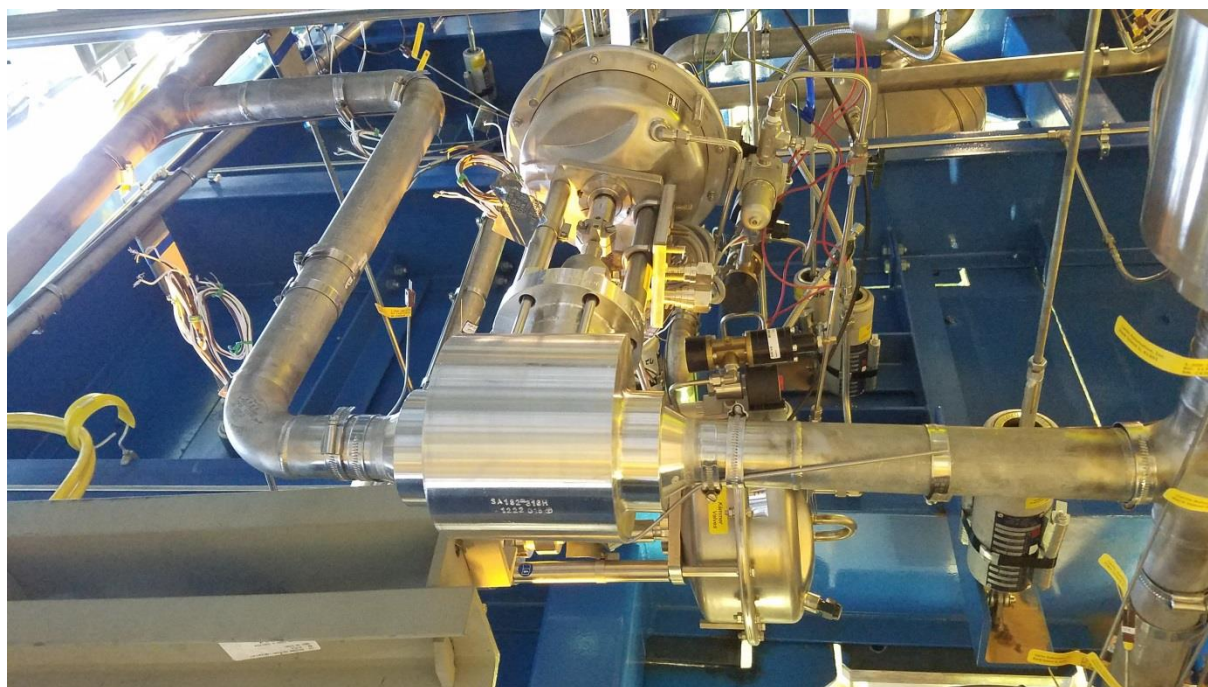
Figure 36 – A photo of a Kammer 1.5" straight valve installed.
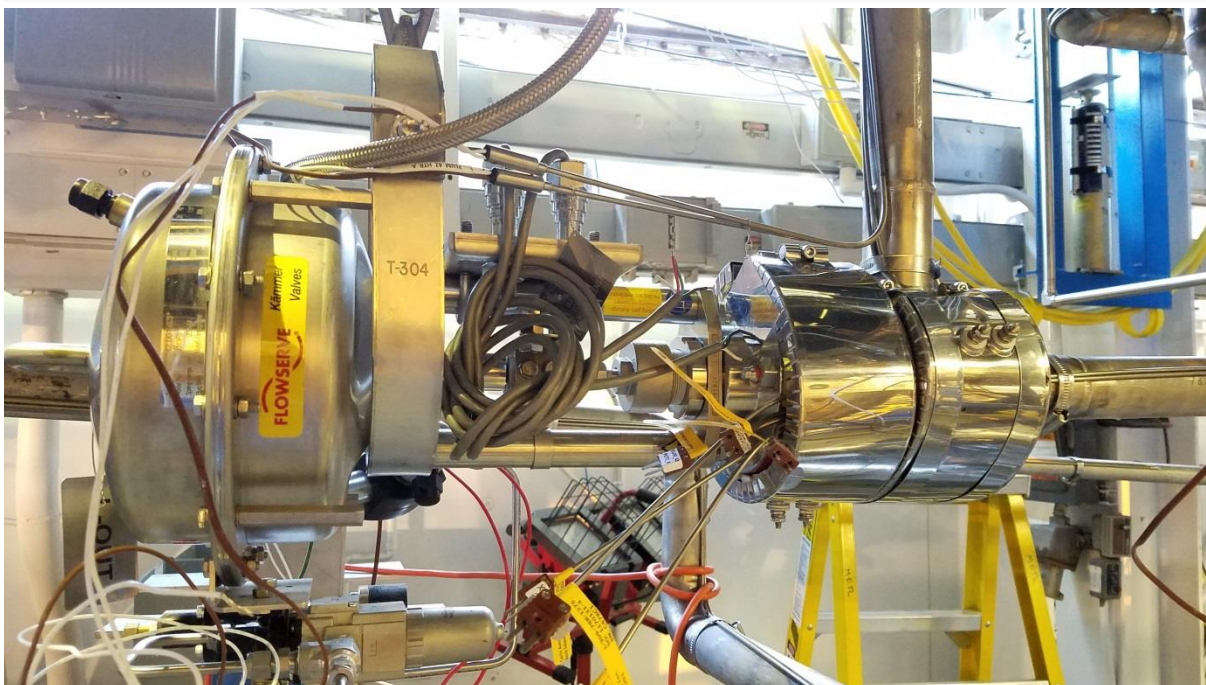
Figure 37 – A photo of a Kammer 1.5" angle valve installed with ceramic band heaters.

The Kammer valves are equipped with ceramic band heaters and are insulated to ensure sodium is liquid before valve actuation. The removable valve insulation uses identical materials and is constructed in a similar fashion as the piping system insulation. However, all of the insulation is contained within a vermiculite jacket and then wrapped with a silicone raincoat. This removable insulation enables efficient and rapid removal/installation of the valves insulation for inspection and repair of hardware internal to the insulation. A picture of Kammer valves equipped with their insulation jacket/raincoat is below in Figure 38.

Figure 38 - Kammer Valve with Insulation.

3.2.3.2 Swagelok Valves

Swagelok valves are used on all parts of the system that do not require 1.5" Schedule 40 piping. Swagelok valves are readily available in sizes up to 1" tube or 0.75" Sch. 40 pipe. These valves come with a welded-bellows seal, are rated for sodium service up to 1200 [°F] and have prepped ends for butt-welded connections. Custom 1" Schedule 40 pipe valves were made available from Swagelok through a special order.

Swagelok valves for liquid sodium service use pipe on the inlet and outlet instead of tube to provide an additional corrosion allowance. All Swagelok valves with piping connections have undergone radiographic analysis to ensure leak-tightness. Valves downstream of the vapor traps and filters utilize the standard tube connections with a wall thickness of 0.065" since sodium corrosion is not an issue.

All 151 Swagelok valves required for the final phase of METL have been delivered to Argonne (Table 4). Photos of electro-pneumatically and manually actuated Swagelok valves installed can be seen in Figure 39 and Figure 40, respectively. All Swagelok valves for Phase I of METL have been installed and operated.

Table 4 – Swagelok valves for METL

Part #	Size	Actuation
SS-8UW-TQ3-HT	0.75" Tube	Manual
SS-12UW-TR3-HT	1" Tube	
SS-12UW-PE3-HT-CZ	0.75" S40 Pipe	
SS-12UW-PG3-HT-CZ	1" S40 Pipe	
IS-SS-12UW-PG3-HT-8C1M-CZ	1" S40 Pipe	Electro-pneumatic
SS-8UW-TQ3-HT-6CM	0.75" Tube	
IS-SS-12UAW-PG3-HT-8C1MCZ	1" S40 Pipe Angled	
IS-SS-12UW-PE3-HT-8C1M-CZ	0.75" S40 Pipe	

Figure 39 - A photo of an electro-pneumatic Swagelok valve with factory-welded 1" Sch. 40 pipe ends. The valve is actuated using ~50 [psig] argon. A position indicator on all electro-pneumatically actuated valves help METL operators verify the state of the valve.

Figure 40 - A photo of a manual Swagelok valve with 1" tube ends.

Swagelok valves are also heated for the same reason as the Kammer valves. However, their body is rectangular so a stainless steel heater block (platen) was machined and strapped to the side of the valve body. Then a cylindrical cartridge heater was inserted into the block along with a thermocouple. Lastly, they were covered with a removable insulation jacket with identical construction to that of the Kammer valves. Pictures of a Swagelok valve with its heater and another valve with its insulation jacket is provided in Figure 41. Adjustments to the heater platens were performed in FY2018 and this work is described below in the commissioning section of the report.
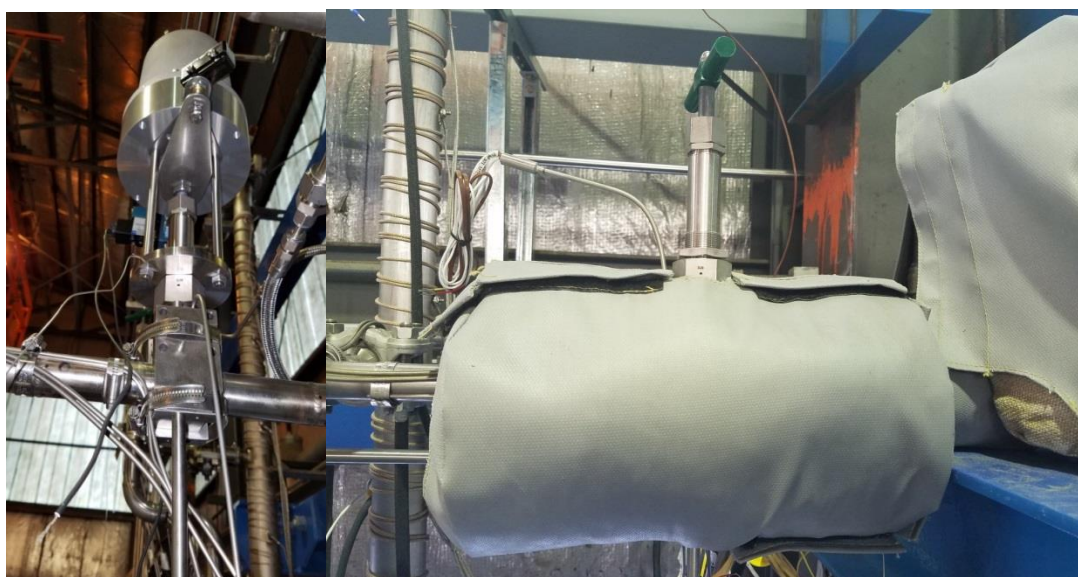
Figure 41 - A Swagelok Valve with Heater (left) and Insulation Jacket (right).

3.2.4   *Dump Tank*

The sodium dump tank, shown in Figure 42, is installed directly on top of the catch pan. The dump tank is 151" long, has an inner diameter of 41", an outer diameter of 42" and a designed capacity of ~840 [gal]. The dump tank is rated for 200 [psig] at 1000 [°F].

There are twenty-one ports located at the top of the dump tank. Each test vessel has an independent drain line that is connected directly to one of these connections. A sodium dump can be carried out for all test vessels simultaneously or for specific vessels in the case of an emergency. To minimize the impact of thermal shock during an emergency drain, the dump tank has thermal baffles (Figure 43), installed in each of the nozzles, to minimize heat transfer from incoming hot sodium with the relatively cooler nozzles. These baffles allow for a 230°C sodium temperature differential to exist between the dump tank and a test vessel during an emergency drain without thermally shocking the dump tank.

Eighteen of the dump tank nozzles were reinforced by the vessel manufacturer (Northland Stainless), in order to withstand the anticipated loads generated by the piping system during changes in temperature. (Three of the nozzles are reserved for instrumentation and do not need to be changed.) The nozzle loads were calculated by Ambitech, using CAESAR-II piping stress analysis software. The dump tank is installed on the catch pan and all of the connections for Phase I have been completed.
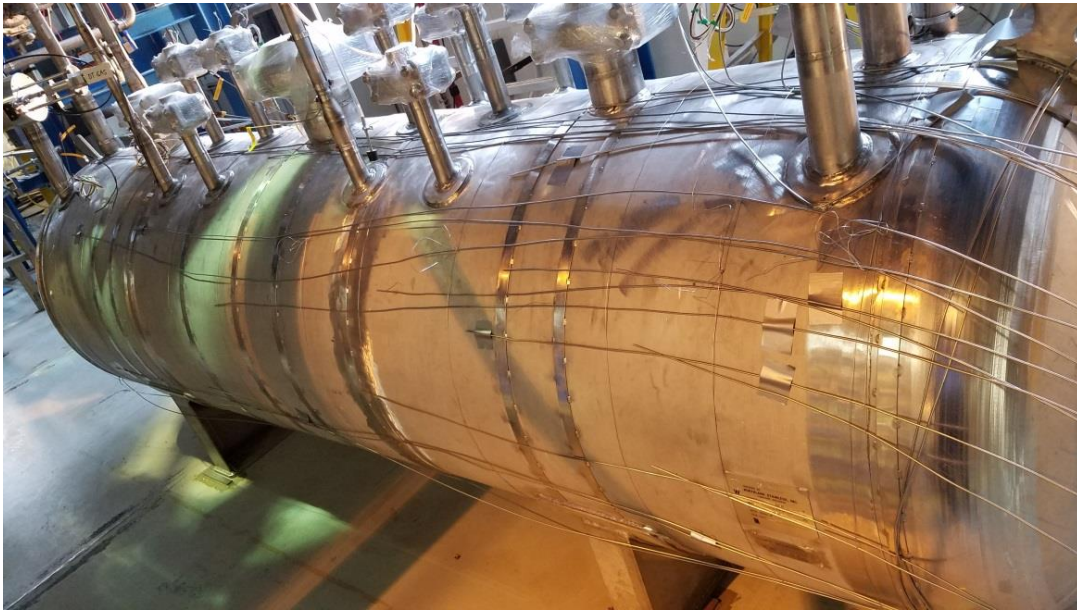
Figure 42 – A photo of the dump tank on the catch pan with thermocouples tack-welded on its' instrumentation bands.

Figure 43 – Dump Tank Thermal Baffles.

The dump tank has over forty thermocouples tack welded to its circumference to monitor and control the temperature. The dump tank is heated by six different heater zones which are constructed from numerous ceramic band heaters as shown below in Figure 44. The dump tank heaters are installed and wired, it has two level sensors inserted and is ready for sodium fill.

Figure 44. The dump tank with thermocouples and ceramic band heaters installed.

3.2.4.1 Dump Tank Enclosure & Thermal Insulation

The dump tank is capable of operating continuously at 1000 [°F]. To maintain this operating temperature; the dump tank has an enclosure equipped with removal panels constructed around it and voids are filled with vermiculite, a pourable thermal insulation as shown in Figure 45. Vermiculite can be vacuumed out and the panels of the enclosure are easily removed to provide access to heaters, thermocouples or instrumentation located on the outside of the tank. It is estimated that the dump tank filled with 800 [gal] of sodium can be heated from room temperature to 1000 [°F] in about four days using this heater/insulation configuration.

Figure 45 – Dump tank enclosure filled with vermiculite thermal insulation. Dump tank nozzles shown penetrating the thermal insulation.

Piping systems and equipment that experience a large range of temperatures must be allowed to expand and contract to ensure the mechanical stress doesn't exceed the materials' limit. Therefore, anchor points are minimized so the system is allowed to freely move. The Dump Tank is a large enough vessel that is expected to experience significant growth and contraction (upwards of an inch). Due to this, the dump tank cannot act as a true anchor point and requires free movement.

To accommodate this, restraints were welded to the catch pan around the feet of the dump tank. As illustrated below in Figure 46, the feet on the right are restrained on three sides and the left

feet are restrained on one side. This allows the dump tank to expand right to left (east to west in reality) without becoming unaligned.

GUIDED END
(2 BARS REQ'D)

SIDE VIEW
SCALE 1 / 20

F

CAPTURED END
(6 BARS REQ'D)

CAPTURED END
(6 BARS REQ'D)

BOTTOM VIEW
SCALE 1 / 20

E
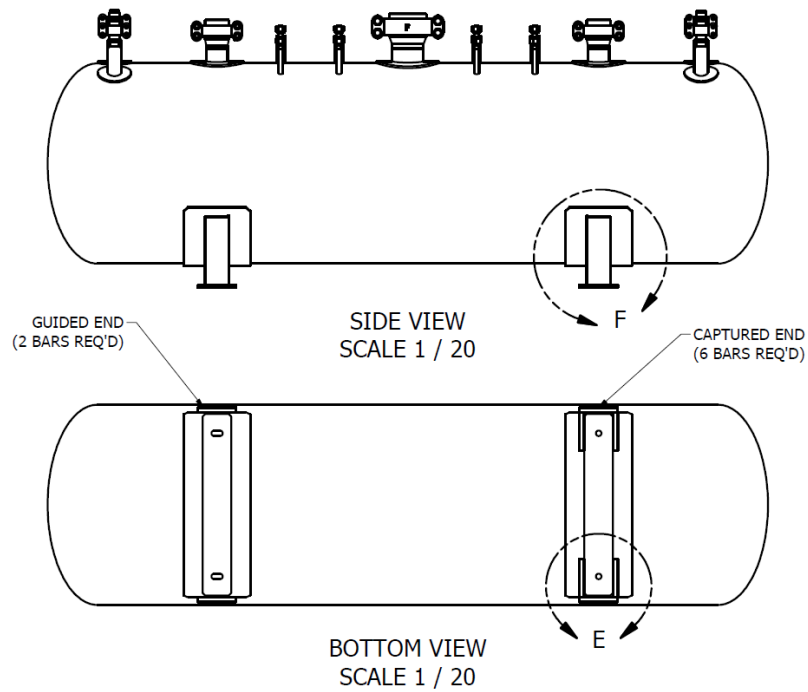
Figure 46 – A photo of the dump tanks' restraints (13).

3.2.5   *Level Sensors*

It is important to monitor the sodium level in both the dump tank and the expansion tank. Different types of level sensing technologies were explored for use in METL but it was found that commercially available level sensors (ultrasonic, guided-wave radar, magnetostrictive, capacitive, float, etc.) were unable to operate in a sodium environment at the design temperature of 1000 [°F]. As a result, Argonne has been designing and testing level sensors for use in METL based upon archived recovered level sensor information.

3.2.5.1 Inductive Level Sensors

Inductive level sensors have been successfully used in high-temperature sodium systems in the past. As seen in Figure 47, the sensor consists of two bifilar coils contained within a stainless steel thimble that can be submerged in sodium. One of the coils is connected to a signal generator while the other coil is connected to a sensitive voltmeter or oscilloscope. Figure 48 shows how the magnetic field produced by the sensor is altered by the presence of an electrically-conductive, non-magnetic liquid metal. The linear, repeatable changes to the circuit can be measured and calibrated to indicate sodium level within METL.
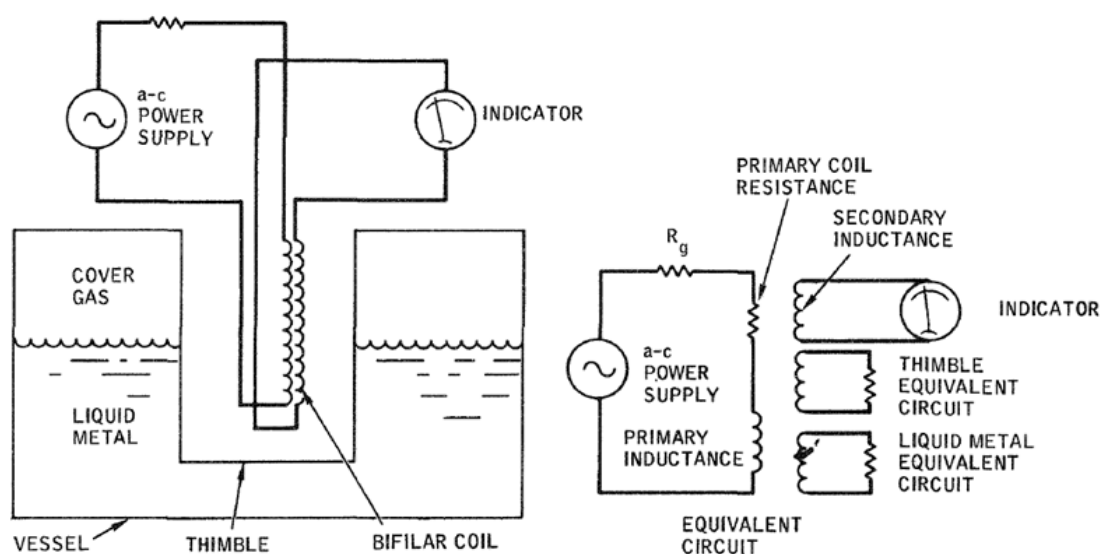
Figure 47 – A diagram showing the operation of an inductive level sensor (1).
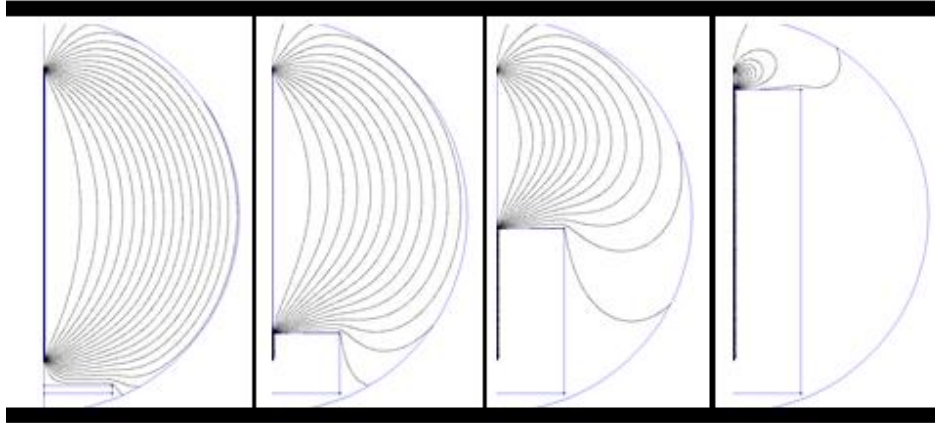
Figure 48 – A picture depicting how sodium level affects the magnetic field produced an inductive level sensor. The changes to the magnetic circuit can be calibrated to determine sodium level. These pictures were produced using FEMM.

The first prototype sensor consisted of two wire coils on a ceramic core. Preliminary level sensor tests used an aluminum tube as a proxy for liquid sodium. As the aluminum tube was moved up or down with respect to the coils, there was a noticeable change in the output of the sensor. As shown in Figure 50, the output signal was sensitive to the operating frequency of the AC power supply and it was found that an operating frequency of ~3.8 [kHz] provided the maximum change in signal. Figure 51 plots the change in signal versus the height of the aluminum tube and the results yield a strong linear relationship. To help ensure the safety and performance of the inductive level sensors, the 316 stainless steel thimbles were designed in accordance with thermowell code ASME PTC 19.3 TW-2010.

Figure 49 – A photo of the experimental setup being used to benchmark an inductive level sensor.
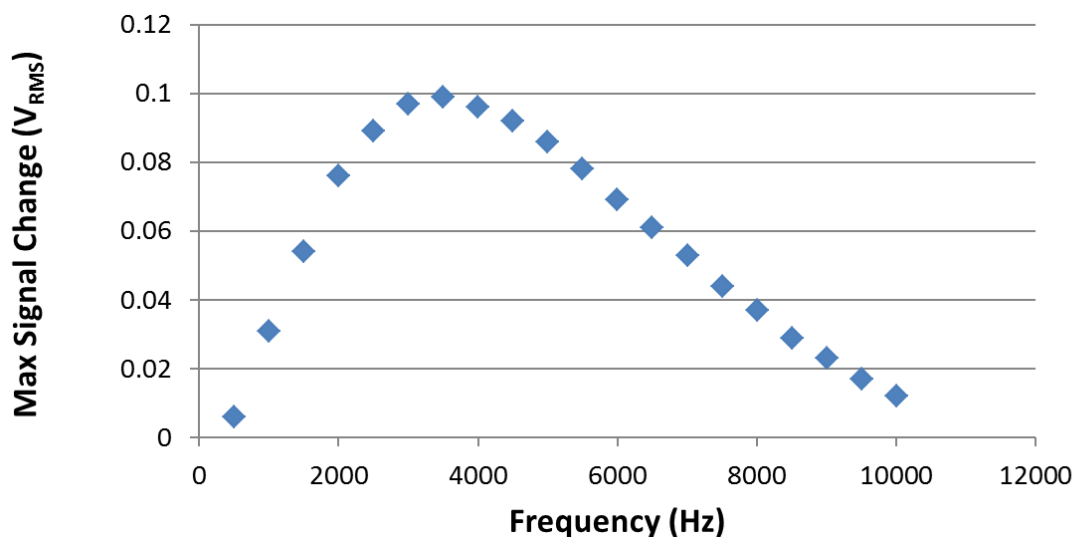
Figure 50 – The maximum change in the output signal as a function of operating frequency.
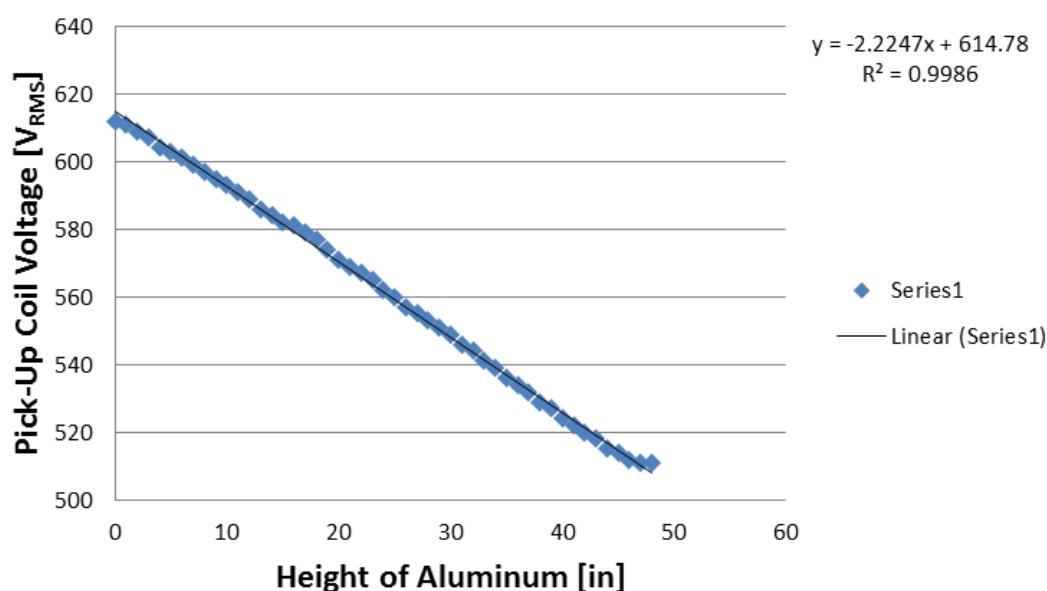
Figure 51 – Initial data from the inductive level sensor tests.

A more robust sensor was desired for in-service METL use. A 304 stainless steel tube replaced the ceramic core to eliminate the concern of breakage. The initial nickel wire was determined to be unsuitable as the Curie point of nickel (354°C) is within the operating temperature range of METL. This type of sensor does not function properly when the temperature of the wires transition past the Curie point. Nickel coated copper (NCC) was chosen for the second wire material as copper does not exhibit a Curie point. The initial NCC sensor was designed for use in the dump tank and had an active coil length of 40 inches. A desire to examine the temperature dependence of the sensor was apparent, so a new testing rig was designed and built. Figure 52

shows the inductive level sensor testing rig built in the high bay of B308. The rig consists of a 1" ID 304 stainless steel tube to mock a sealed thimble, a 40" long aluminum cylinder surrounding the thimble to mock the sodium, two mineral insulated cable heaters, and insulation. The sensor was free to move axially in the thimble to mock a change in sodium height. The position of the sensor in relation to the aluminum was controlled by a winch system.

Figure 52 – Inductive Level Sensor Testing Rig.

Ambient temperature testing was completed for the initial sensor in the testing rig. Figure 53 displays calibration data collected during this campaign. The data trend observed was acceptably linear and repeatable. A consequence of the increased wire size and insulation was

a reduction in the number of windings of the primary and secondary coils. This coil winding reduction resulted in a noticeable reduction in sensor signal and accuracy. This undesired effect initiated a search for a wire more appropriate for the application.

Calibration Curve 1/19/2017

$y = -0.5561x + 82.244$
$R^2 = 0.9975$
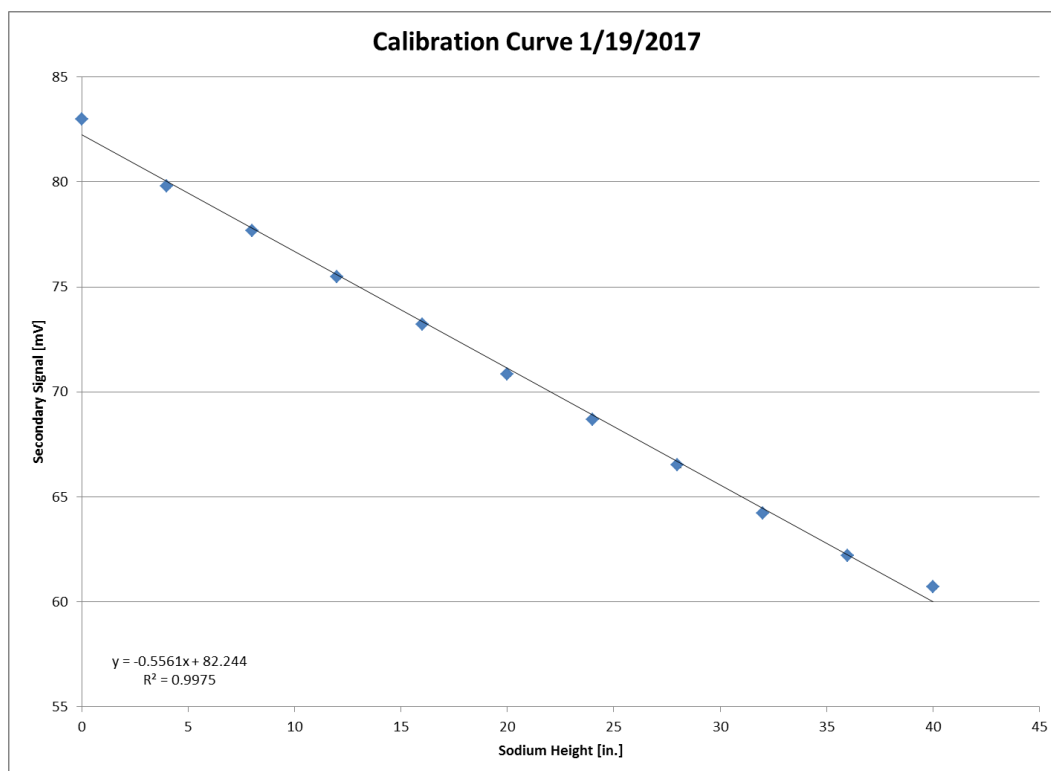
Figure 53 – Initial Level Sensor Ambient Temperature Data.

Constantan was selected to replace the NCC. Constantan has a maximum operating temperature of 1300°F, a Curie point well below the operating temperatures of METL, as well as a low temperature coefficient of resistivity. A new sensor was fabricated using the constantan for both primary and secondary windings. The reduced cross section of the wires allowed for a significant increase in windings. Figure 54 displays ambient temperature data collected using the constantan sensor.
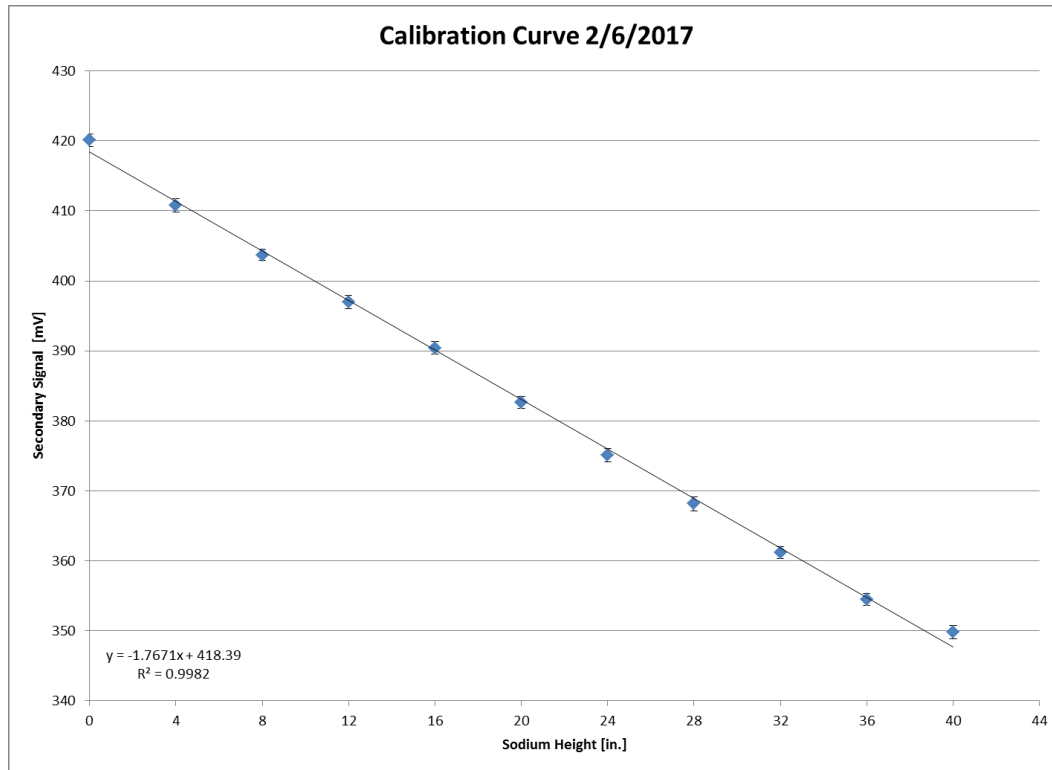
Figure 54 – Updated Dump Tank Level Sensor Ambient Temperature Data.

The signal generated by the constantan sensor was improved by the increased winding count and determined acceptable for use in METL. A second constantan sensor was fabricated for use in the expansion tank with an active winding length of 60". Two 316 stainless steel thimbles were designed and fabricated to house the sensors in the dump tank and expansion tank. Figure 55 displays the drawing for the dump tank thimble. Figure 56 shows the two thimbles installed in the expansion tank and dump tank with the sensors inside of each.

PARTS LIST				
ITEM	QTY	PART NUMBER	DESCRIPTION	MATERIAL
1	1	170622AB-GL	GRAYLOC HUB, MODIFIED	316/316L SS
2	1		BUTT WELD PIPE CAP, 2" SCH 40	316/316L SS
3	1	170622AB-TC	THIMBLE CAP	316/316L SS
4	1	1SCH40X125-01	TRANSITION 1" SCH 40 X 1.25/.12 WALL	316/316L SS
5	1		TUBE, 1.25 O.D. X .12 WALL	316/316L SS
6	1	MHM6(SWM6)	CONAX MULTI-HOLE METAL GLAND SEAL	316L SS
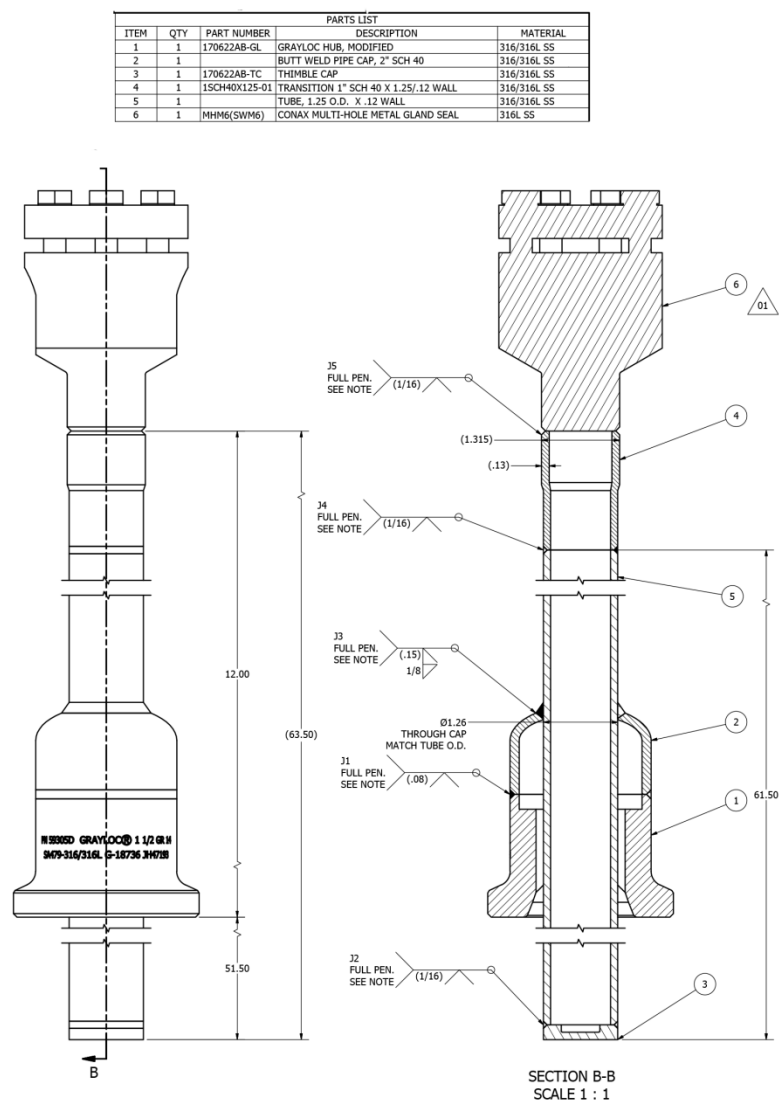
Figure 55 - Inductive Level Sensor Thimble
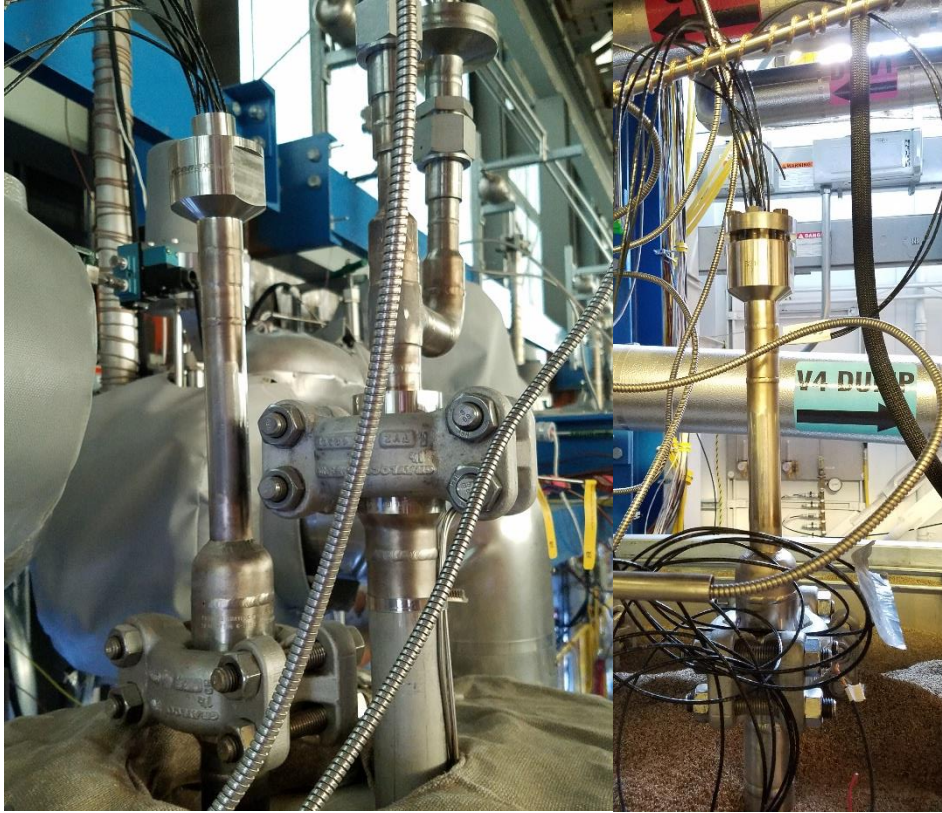
Figure 56 - Expansion Tank (left) and Dump Tank (right) with Inductive Level Sensors

It was desired to further increase the sensors signal and accuracy. To accomplish this a signal amplifier was implemented into the system. This signal amplifier allowed for a greater applied voltage to the power winding of the sensor. Calibration efforts outside of a sodium environment proved to be useful in understanding the function of the sensors as well as determining the optimal electronics setup. Final calibration was decided to be performed during the dump tank sodium fill to ensure the greatest accuracy.

In April 2018, sodium fill was performed by filling the dump tank with (15) 55-gallon barrels of liquid sodium. Each barrel had a finite amount of sodium that was transferred to the dump tank. The amount of sodium transferred was monitored using a drum scale. The mass of each transfer could be used to determine the volume transferred, and therefore the level increase. By operating the inductive level sensor during these dump tank fill procedure, calibration was made possible by monitoring the signal change during each barrel transfer. The processed data from these efforts is displayed in Figure 57.
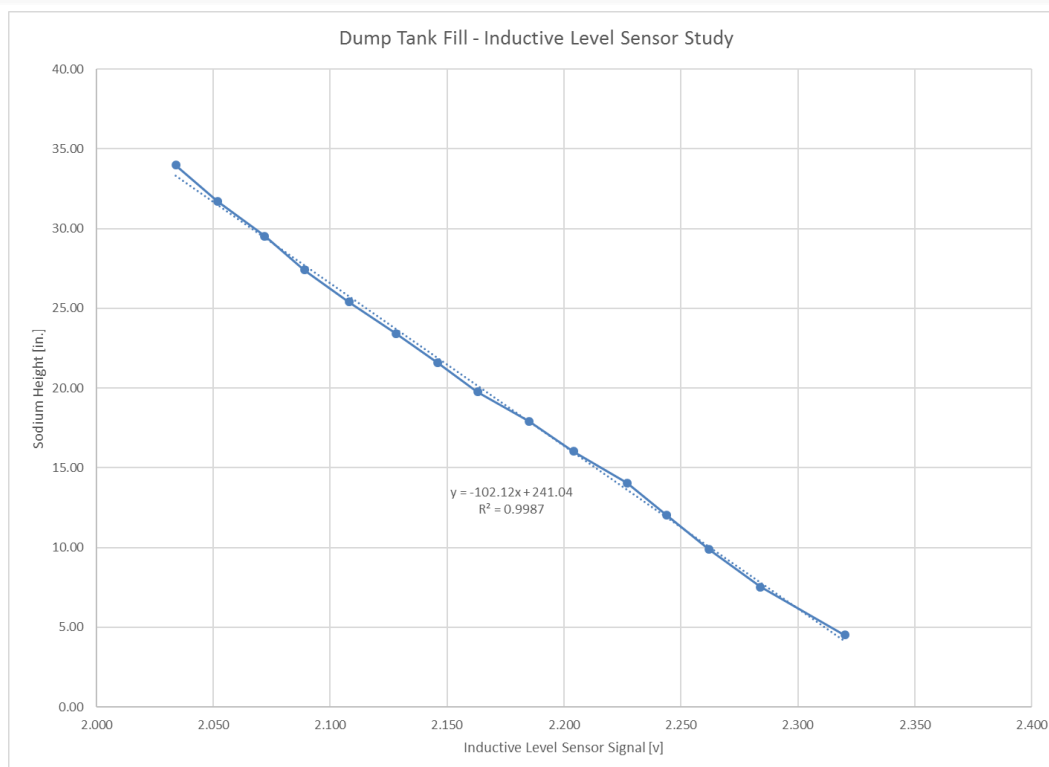
Figure 57 – Dump Tank Sodium Fill Level Sensor Data

While the hand wound constantan sensor performed acceptably during the dump tank sodium fill, there was a desire to increase the robustness of the sensor. A literature review indicated that inductive level sensors historically were fabricated in a stainless steel sheathed mineral insulated (MI) coil. These sensors are less likely to short out or fail. Idaho Laboratories Corporation was identified as a manufacturer capable of producing such a coil. Four coils were procured and are undergoing preliminary testing. These sensors are intended to replace the constantan sensor if failure occurs.

3.2.5.2 Differential Pressure Level Sensor

Differential pressure level sensors are also used within the METL dump tank and expansion tank. As seen in Figure 58, this type of sensor operates by measuring the pressure difference between the gas space and the bottom of an argon-filled dip tube. Also, the density of sodium as a function of temperature is very well known and acceleration due to gravity is assumed constant; so the simple hydraulic equation (EQ:1) below can be utilized to compute the height of the sodium

$$h = \frac{\Delta P}{g \rho} \qquad \text{EQ:1}$$

Where:
- ΔP = differential pressure
- g = gravitational constant

- h = height of the fluid
- ρ = density of the fluid

The differential pressure sensor is not only an accurate method of level detection but can be used to calibrate other level sensors as well. In FY2016, Argonne engineers approved drawings developed by a vendor for the creation of a differential pressure sensor (ΔP gauge) that has sufficient resolution (~1/4 [in-H_2O]) to be used as a level sensor. Each differential pressure transmitter has two NaK (sodium potassium alloy) filled capillary lines which were connected to their respective process port via 1" VCR connection.
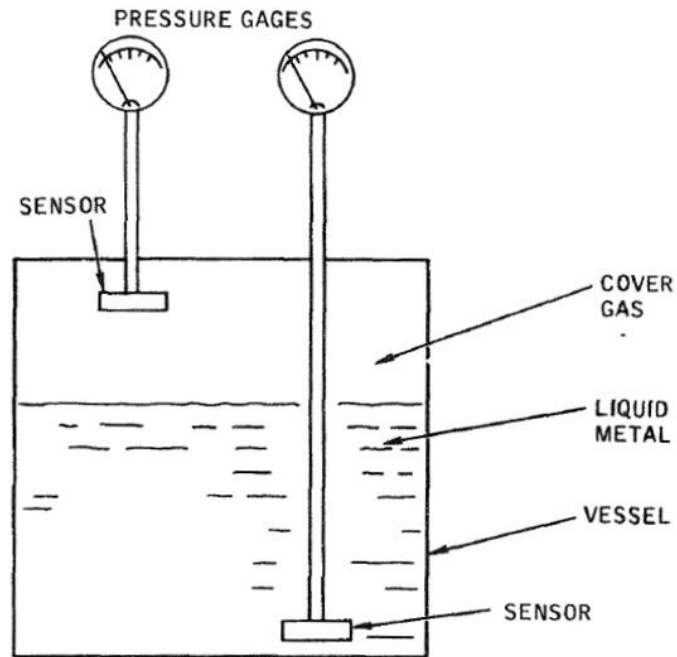
Figure 58 – A schematic showing the operating principle of a differential pressure level sensor (1).
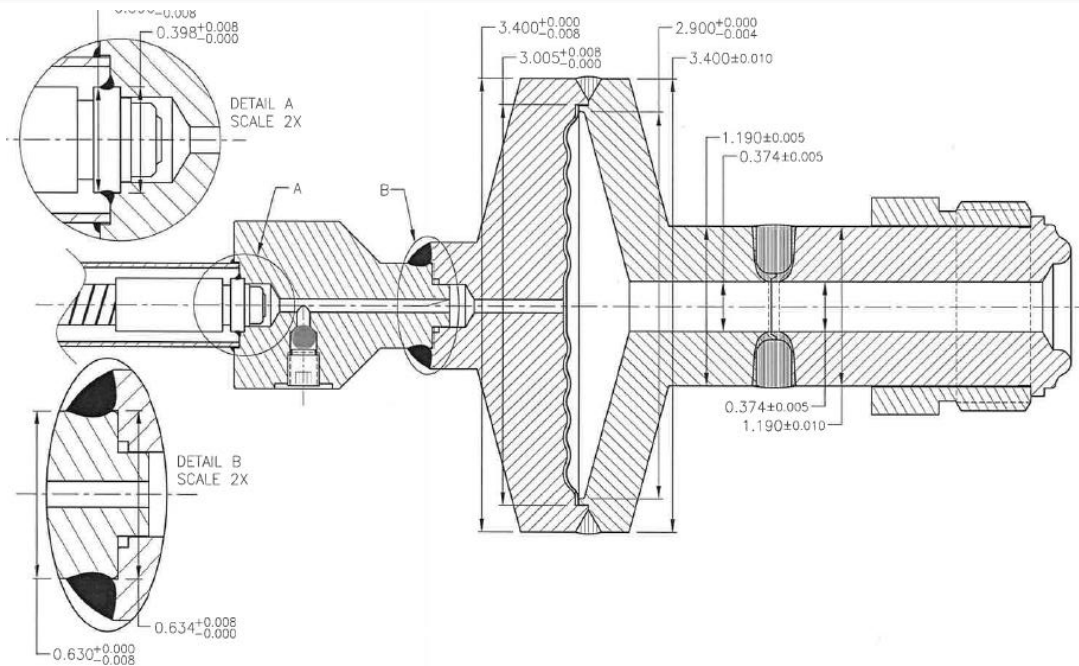
Figure 59 - A drawing of the NaK-filled differential pressure transducer that is connected to the dump tank and expansion tank gas space using VCR fittings. The large diaphragm on this sensor should offer ΔP resolution ≈ 0.25 [in-H₂O] for more accurate sodium level determination (12).

The ΔP gauge can be connected to the gas space of the dump tank and expansion tank using VCR fittings, as shown above in Figure 59. The VCR connections are rated to 537°C and are more compact than Grayloc connections. Other than the two VCR connections, the ΔP gauge has 100% welded construction. A drawing of the ΔP gauge assembly (transmitter, capillary lines, diaphragm seals, and 1" VCR connections) is shown below in Figure 60.
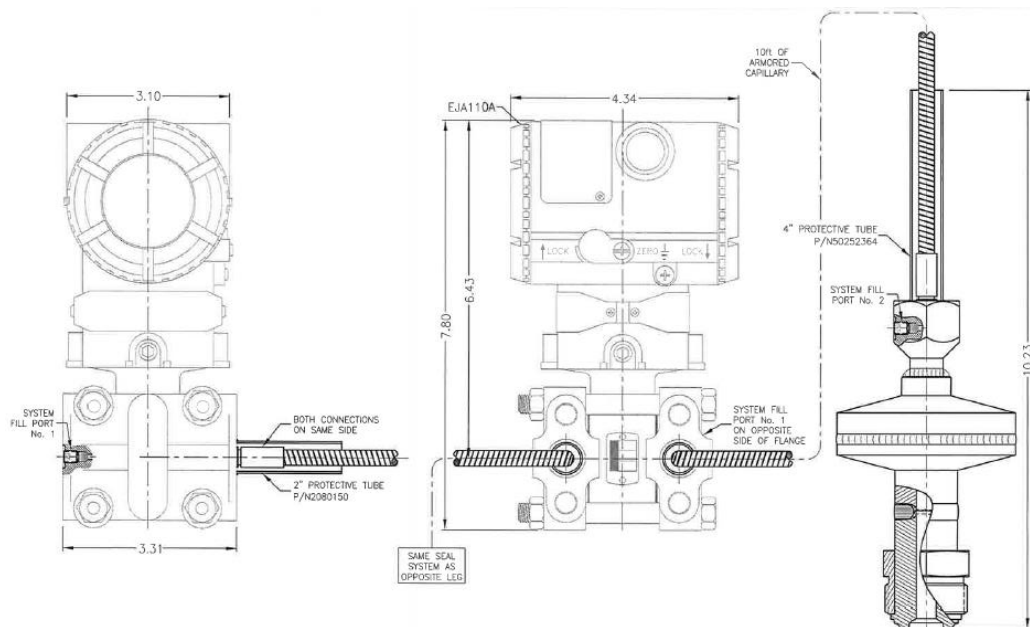
Figure 60 – ΔP gauge Assembly for Level Measurement in the Dump Tank and Expansion Tank (12).

Two primary drawbacks of the differential pressure sensor is the fact it requires two connections and one of the connections must be made at the bottom of a vessel. These shortcomings are addressed by utilizing a dip tube with a "Tee" and "Tube in Pipe Tee" connection. An engineering drawing of the dip tube is illustrated below and subsequently explained.

ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	160906DK-GL	GRAYLOC HUB, MACHINED
2	1	107437-A MOD 2	
3	1	316L-16TB7-6-12	REDUCER, 1" x 3/4" TUBE, BUTT-WELD
4	2	SS-16-VCR-3-16TB7	ACIS data in IGES format
5	2	SS-16-VCR-1	VCR FEMALE NUT, 1"
6	1	MCMASTER CARR 45555K583 OR EQUIVALENT	PIPE CAP, 1"
7	1	MCMASTER CARR 89785K861 OR EQUIVALENT	3/4" TUBE, .083 WALL
8	1	ASME B16.9 Long Radius 90 Deg Elbow (Inch) 1 x 0.133	Wrought Buttwelding Fitting - Long radius 90 Deg Elbow - Inch
9	1	ASME B16.9 Straight Tee 1 x 0.133	Wrought Buttwelding Fitting - Straight Tee .Inch
10	2.000 in	ANSI/ASME B36.19M Pipe 1 - Schedule 40S - 2	Stainless Steel Pipe

Figure 61. Differential Pressure Level Sensor Dip Tube (12)

An adapter is connected to the "on-the-run" connection of the "tube in pipe tee" connection. The adapter is essentially another tee fitting that allows for one connection of the differential pressure sensor and another for the argon supply. Argon is allowed to slowly flow through the adapter and through the vertical tube which is then pushed to the bottom of the vessel. Argon bubbles then rise through the liquid sodium to the top of the vessel eventually ending in the vapor space. This allows the high-side of the sensor to effectively measure the pressure at the bottom of a vessel without requiring the sensor to actually be placed in the vessel.

The branch of the "tube in pipe tee" is connected to the low-side of the differential pressure sensor. Holes were drilled into the Grayloc hub to allow the sensor to measure the vapor pressure inside of the vessel. In conclusion two measurements are made to result in a differential pressure while only requiring one port connection on the vessel and the sensor in its entirety remains outside of the vessel.
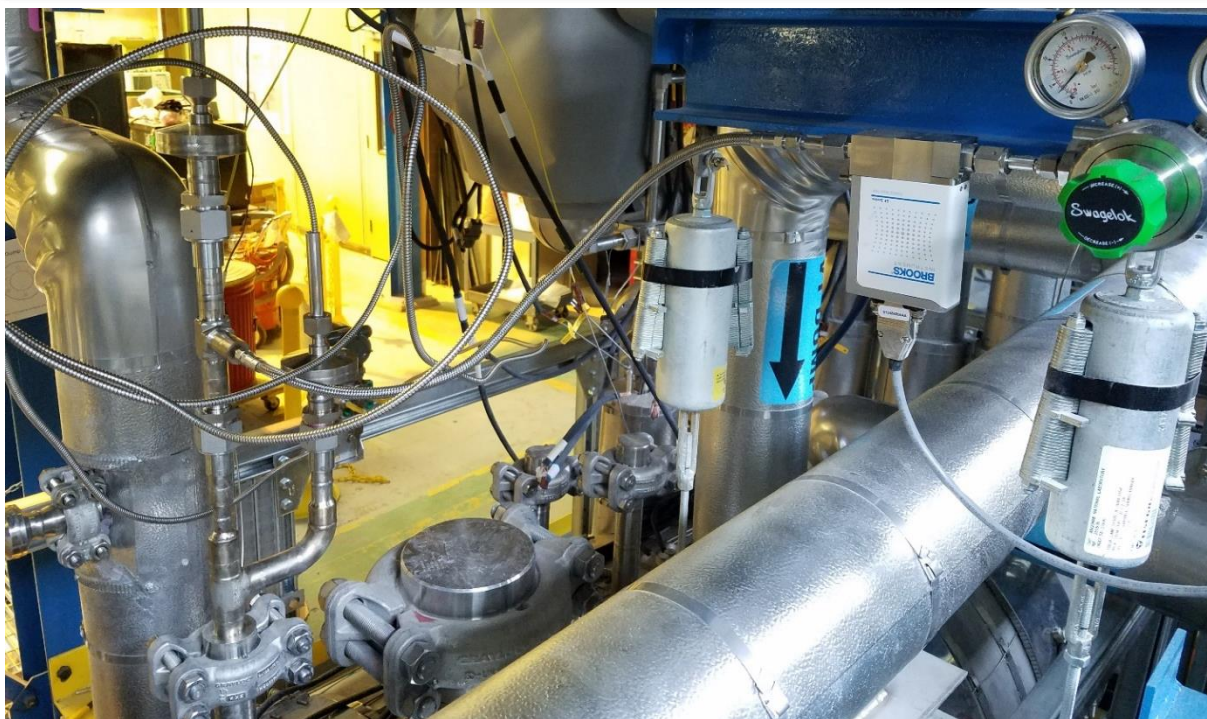
Figure 62. Differential Pressure Level Sensor Installed in the Dump Tank

The differential pressure level sensor requires some additional hardware to control the Argon flow through the dip tube. Shown above in Figure 62, a regulator to drops Argon supply pressure (green handled device) that is supplied to the mass flow controller. The mass flow controller receives a signal from the control program to throttle its opening to "bubble" Argon gas through the bottom of the dip tube.

3.2.6   *Purification & Diagnostic System*

High concentrations of oxygen or other impurities within the sodium can accelerate corrosion or cause unwanted plugging. Impurities can be introduced into the system whenever new components are installed, if leaks occur or when more sodium is added to the dump tank.

In order to control and measure the amount of impurities in the sodium; METL has   a purification and diagnostic system that consists of a cold trap, a plugging meter, an economizer, two EM pumps, two flowmeters, four pressure transducers; this equipment is depicted in Figure 63. All components within the purification system are rated for temperatures ranging from 0 - 1000 [°F] and pressures ranging from 1E-4 [Torr] to a maximum of 100 [psig] in accordance with the ASME codes.
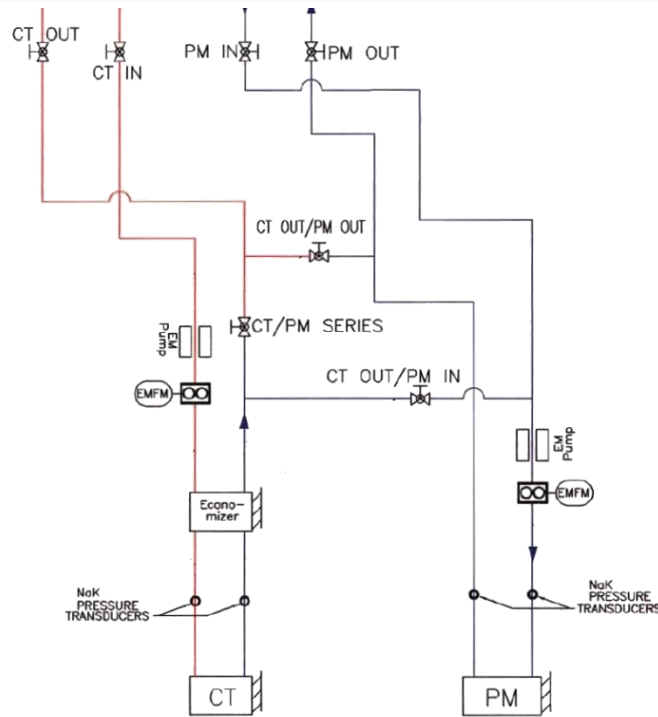
Figure 63 – A detail of the METL P&ID showing the functional layout of the purification system. The cold trap is abbreviated as "CT" and the plugging meter is abbreviated as "PM" (13).

The purification system is designed to work in four different operational modes:

1) *Purification mode* - Only the cold trap is in use. This mode can be used after a test article has been inserted or removed since there could be a higher impurity concentration and a greater likelihood of clogging the plugging meter.

2) *Measuring mode* - Only the plugging meter is in use. This mode can only be used to monitor the impurity levels within the flowing sodium.

3) *Purification/Measuring mode* - Both the cold trap and the plugging meter are in use while connected to the main loop in parallel. This mode may be used to simultaneously clean and monitor the bulk sodium.

4) *Test mode* - Both the cold trap and the plugging meter are connected in series. This mode can be used to determine the effectiveness of the cold trap at different temperatures and flow rates.

3.2.6.1 Cold Trap

The cold trap operates by cooling a small fraction of the flow in the main piping system to temperatures just above the freezing point of sodium. At these colder temperatures the solubility of oxides, hydroxides or other impurities is drastically reduced. If dirty sodium enters the cold trap it becomes super saturated with the impurity as it is cooled. The impurities are then

precipitated out of solution and adhere to the stainless steel mesh packing within the volume of the cold trap. The clean, cool sodium can then reenter the main loop as the cleaning process continues. It is expected that sodium leaving the cold trap will contain oxygen concentrations under five parts per million. See Figure 64 for the saturated oxygen concentration of sodium.

In order to cool the sodium, the cold trap loop relies on both an economizer and a blower to push ambient air over the cold traps heat transfer fins. Together, these two components can reduce sodium temperatures from a maximum of 538 [°C] / 1000° [F] to the plugging temperature (110-150 [°C]) at a nominal flow rate of 1 [gpm].

Cold Trap Design Parameters:

Temperature:
        Minimum operating temperature: 110 [°C] / 230 [°F]
        Maximum operating temperature: 538[°C] / 1000 [°F]

Flow:
        Minimum: 0.2 [gpm]
        Maximum: 2 [gpm]
        Nominal: 1 [gpm]

Impurity concentration after purification:
        Oxygen < 5 [ppm]
        Hydrogen < 5 [ppm]

Solubility of Oxygen in Sodium
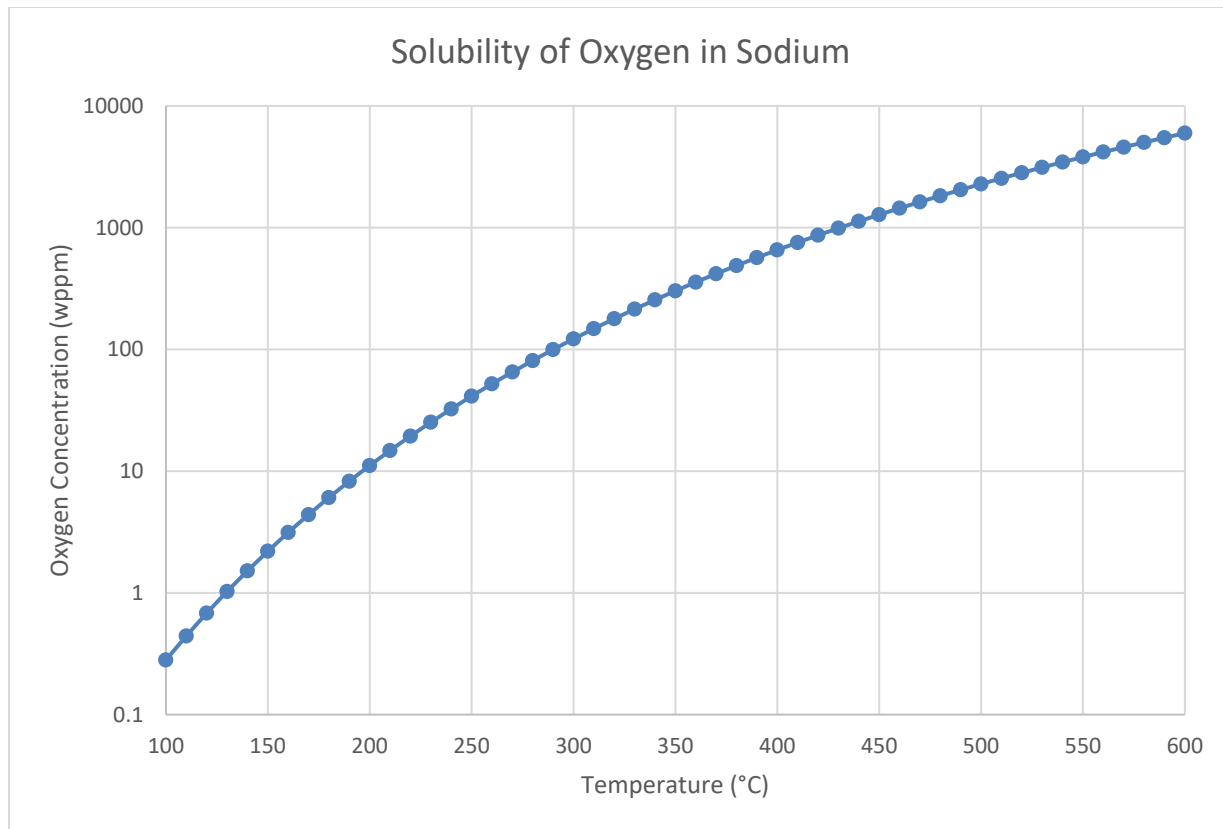
Figure 64 – Solubility of oxygen in sodium as a function of temperature.

During FY2014, the cold trap was fabricated and delivered. The size of the air inlet at the bottom of the cold trap was increased to accommodate an anticipated 1500-2000 [CFM] air flow rate. Finally, a sheet metal manifold was fabricated by ANL-CS to duct the cooling air out of the Bldg. 308 hi-bay.

During FY2015 the cold trap was sent to Ability Engineering to have the inlet and outlet nozzles reinforced to withstand the anticipated piping loads due to thermal expansion and contraction. Figure 65 shows a picture of the cold trap nozzles before and after reinforcement. The cold trap is currently installed in METL as shown in Figure 66.

Figure 65 - Photos of the cold trap nozzles before (TOP) and after (BOTTOM) reinforcement.

The cold trap has many type-K thermocouples welded inside of it so that this instrumentation is in contact with the flowing sodium for precise measurement and control. Additionally, the blower utilized to deliver cooling air to the cold trap is equipped with a variable frequency drive to provide further control of the cold traps operating conditions. To monitor the amount of contamination retained in the cold trap, inlet and outlet pressures of the cold trap are measured and logged.

Figure 66 – Cold Trap Welded into the METL

The completed cold trap is pictured below in Figure 67. The blower delivers ambient air to the bottom of the cold trap. The air absorbs heat from the cold trap which is filled with molten sodium. The air is then exhausted through the top duct. Unlike the plugging meter, the cold traps discharged air is expected to be quite hot and therefore the ducting was routed to vent the air outside of the building. Additionally, the cold trap requires a larger volumetric flow rate of air to control its temperature.

Figure 67 - Completed Cold Trap

Figure 67 also shows that the cold trap is enclosed by a stainless steel container. This container is snapped together and under it is a removable insulation jacket with identical construction to the valves. The rationale for the removable insulation jacket is the cold trap is heated with ceramic band heaters. The ceramic band heaters are expected to require more maintenance and attention than the mineral insulated cable heaters. Without a removable insulation jacket; repair and maintenance time on the heaters would be primary consumed by insulation removal and re-installation.

3.2.6.2 Economizer

As shown in Figure 68, the economizer is a ~ 40 [ft] pipe-in-pipe helical coil counter-flow heat exchanger that was designed to recuperate some of the heat losses incurred from the cold trapping process. Hot, unpurified sodium from the main loop flows towards the cold trap in the inner tube of the economizer. Cold, purified sodium leaving the cold trap returns to the main loop by flowing along the opposite direction within the annular region, on the outside of the helical shell. In summary, this counter-current flow pre-cools in-coming cold trap sodium and pre-heats out-going sodium.

As shown in Figure 69, the economizer is installed within a custom enclosure designed to keep the coils at the appropriate elevation and spacing. A centering frame within the enclosure prevents the economizer from shifting due to thermal expansion/contraction during operation.

During FY2015, the vendor delivered the completed economizer and it was installed in FY2016 (Figure 70). The economizer has its MI cable heaters and thermocouples installed. Similar to the Dump Tank, the economizer is housed in an enclosure filled with vermiculite to act as insulation. In conclusion, the economizer has been completed and is ready for operation.

Economizer Design Parameters:

Hot side inlet temperature: 1000 [°F] / 538 [°C]

Hot side outlet temperature: 273 [°F] / 134 [°C]

Cold side inlet temperature: 240 [°F] / 116 [°C]

Cold side outlet temperature: 967 [°F] / 519 [°C]

Flow rate: 0.2 - 2 [gpm]

Figure 68 - A photo of the completed economizer coil at ANL Central Shops.
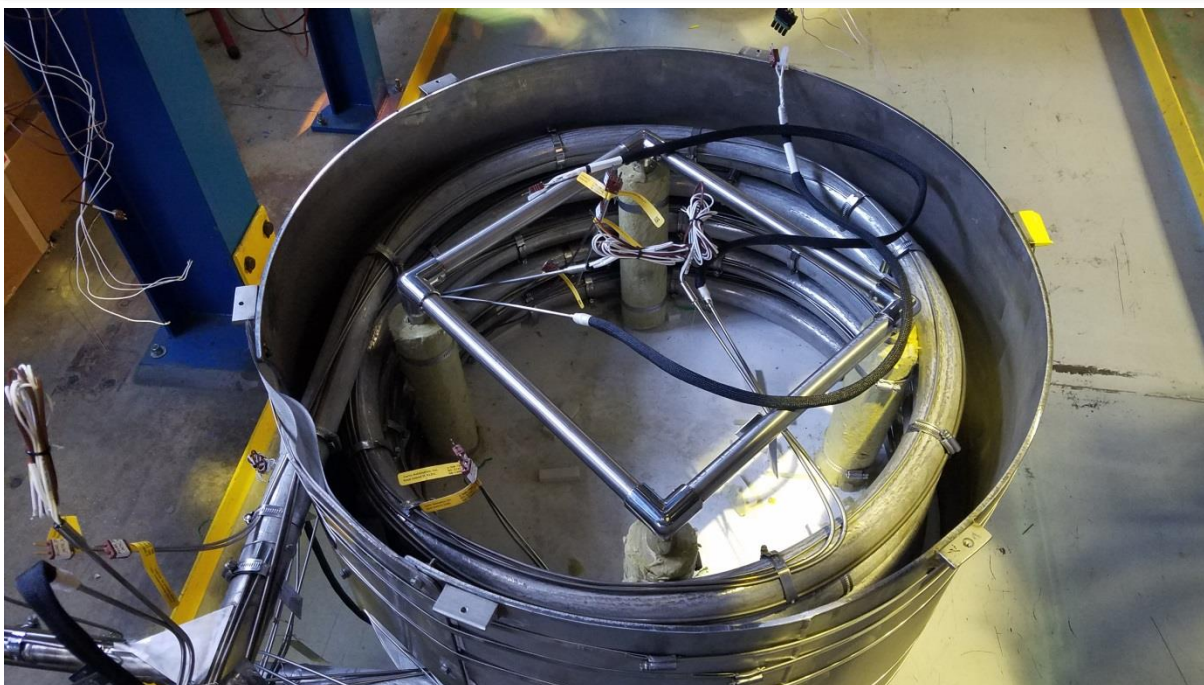
Figure 69 - A photo of the economizer within the tank. The economizer coils are centered using the internal frame. To prevent metal-on-metal rubbing, the internal frame is padded with high-temperature fiberglass insulation.

Figure 70 – The economizer filled with vermiculite insulation.

3.2.6.3 Plugging Meter

The completed plugging meter was delivered to Argonne in FY2014 along with the associated blower fan and variable frequency drive (VFD). The plugging meter measures sodium impurity levels (a conceptual depiction of a plugging meter can be seen in Figure 71).

During operation, sodium enters the plugging meter from the main loop. This hot sodium is cooled below the saturation temperature of any impurities that it may contain. These impurities precipitate out of solution and gradually plug an orifice plate. While the flow rate is dropping, the cooling air flow is gradually reduced so that the temperature of the sodium at the orifice can slowly increase. Impurities continue to precipitate out of solution and contribute to plugging as long as the sodium is below its saturation temperature for a given impurity level. When the sodium at the orifice reheats to a certain temperature the plug will begin to dissolve and the flow rate will return to normal (3).

The saturation temperature of the impurity corresponds to the minimum flow rate just as the plug begins to re-dissolve into solution. It is at this point that, "since the rate of change of flow is zero, the precipitation and dissolution rates are equal, and, by definition, the temperature at this condition is the equilibrium saturation temperature of the impurity in solution (4)."

Unfortunately, a plugging meter is non-discriminant so any impurity in the system could plug the flow restriction, not just oxygen. Nonetheless, it is typically assumed that the predominant impurity is oxygen. Therefore, once the saturation temperature has been measured, the Noden correlation (Figure 64) or RDT standard can be used to determine the oxygen concentration of the sodium.
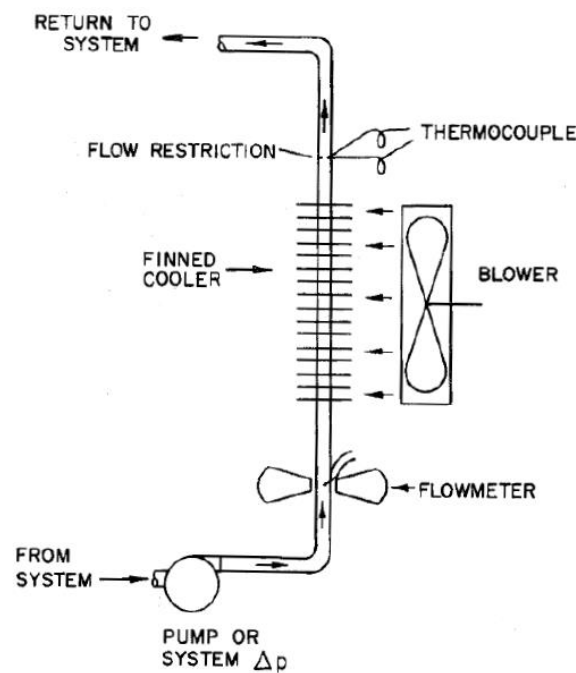
Figure 71 – A conceptual depiction of a plugging meter (5).

The METL plugging meter has a long tube-in-pipe design and is shown below in Figure 72. The upper section of the plugging meter is an economizer that recuperates heat when incoming and outgoing sodium pass through it. The incoming sodium is cooled down to the plugging temperature by the air from the blower as it flows down along the annular region of the plugging meter. Different sodium plugging temperatures can be reached by adjusting either the flow rate of the air or the sodium.

Plugging Meter Design Parameters:

Inlet temperature: 1000 [°F] / 538 [°C]

Outlet temperature: 859 [°F] / 459 [°C]

Coldest temperature: 228 [°F] / 109 [°C] (near the orifice plate)

Cold side outlet temperature: 967 [°F] / 519 [°C]

Nominal flow rate: 0.15 [gpm]

Figure 72 – Plugging Meter Installed into the METL with its' blower and VFD.

3.2.6.4 Thermal Mixing Tees

Since the sodium leaving the cold trap and plugging meter is relatively colder than the main loop, thermal mixing tees are needed to mitigate the harmful effects associated with thermal shock and thermal striping. Two thermal mixing tees were designed, fabricated, and delivered in FY2014. A photo of a completed mixing tee installed in the METL piping system can be seen in Figure 73.

Two tees are installed in the main piping system. One of the mixing tees is located where the sodium leaving the economizer reenters the main loop. Another identical mixing tee is similarly positioned downstream of the plugging meter. In Figure 73, the branch of the thermal mixing tee is connected to the outlet of the plugging meter loop with the run portion of the tee connected to the primary loop.

Figure 73 – A photo of one of the thermal mixing tees installed into the METL piping.

3.2.7 Test Vessels

In May 2015, Northland Stainless was awarded the contract to build two 18" vessels and two 28" vessels for Phase I of METL. Since then, Argonne engineers worked with the vessel fabricator and offered feedback on drawings, calculations, and welding procedures.

Major changes to the new 18" vessels that are installed in METL compared to previous designs are:

a) Reinforced nozzles to withstand piping loads from thermal expansion and contraction

b) Modified nozzle orientation to conserve space on top of the mezzanine

c) Updated flange design that facilitates installation and removal of test articles

d) Supported via side lugs instead of legs.

All of the vessels have been fabricated and are shown being staged at Northland Stainless in Figure 74. The vessels were to be fabricated using only 304 stainless steel material. After arrival of the test vessels, the manufacturer stated that there was a documentation issue and one of the 18" vessels' body was constructed of 304 stainless while, its' neck flange is composed of 316 stainless. The fabricator was unaware of the documentation error and believed both the body and flange were composed of 304 stainless steel so, they proceeded to weld the pieces together. Although, 316 stainless steel is generally considered a higher quality material due to the presence of molybdenum to prevent corrosion and the ASME pressure vessel code views both materials to have the same coefficient of thermal expansion; a more detailed analysis of the difference in the 304/316 stainless steel behavior was pursued by Argonne engineers. Therefore, a stress analysis of the vessels with all 304 stainless steel construction and 304/316 construction was pursued under steady state and transient conditions. The ANSYS transient and steady state analysis revealed the stress induced by the different stainless steel (304/316 SS) thermal

expansion coefficients would not yield any detrimental outcomes so, the second 18" vessel was re-certified and installed into METL.

Figure 74 – A photo of the vessels during inspection at Northland Stainless.

All of the new test vessels perform the same function as previously anticipated. The 18" test vessels are intended for the study of smaller components that do not require a large test vessel. The 18" test vessels have a maximum temperature of 1000 [°F]. The total volume in the vessel is about 40 [gal].

Similarly, the 28" test vessels, will be used to conduct performance testing of actual and/or prototypical components. These larger vessels have a maximum operating temperature of 1,200 [°F]. The total volume in the vessel is about 170 [gal].

All test vessels are designed so that different types of assemblies can be easily tested by connecting to vessels using standard flange sizes. The top rim of the vessel is designed to accommodate the flexi-cask system, a device that will be used for test article removal and insertion. Currently, all of the vessels have been installed into the METL piping system on the mezzanine as shown in Figure 75.

Figure 75 – Vessels installed on the mezzanine.

The 18" vessels' body does not break the plane of the mezzanine however, the larger 28" vessel bodies actually protrudes through the METL mezzanine deck as shown in Figure 76. Like the dump tank, all of the vessels have thermocouples tack welded onto their "instrumentation bands" for monitoring and controlling the heaters. One of the 18" and 28" test vessels with thermocouples installed can be seen in Figure 77. Each vessel is equipped with 36 thermocouples placed strategically on the vessel to monitor stress concentrations and heater output.

Figure 76 – 28" Vessels protruding the mezzanine of the METL.
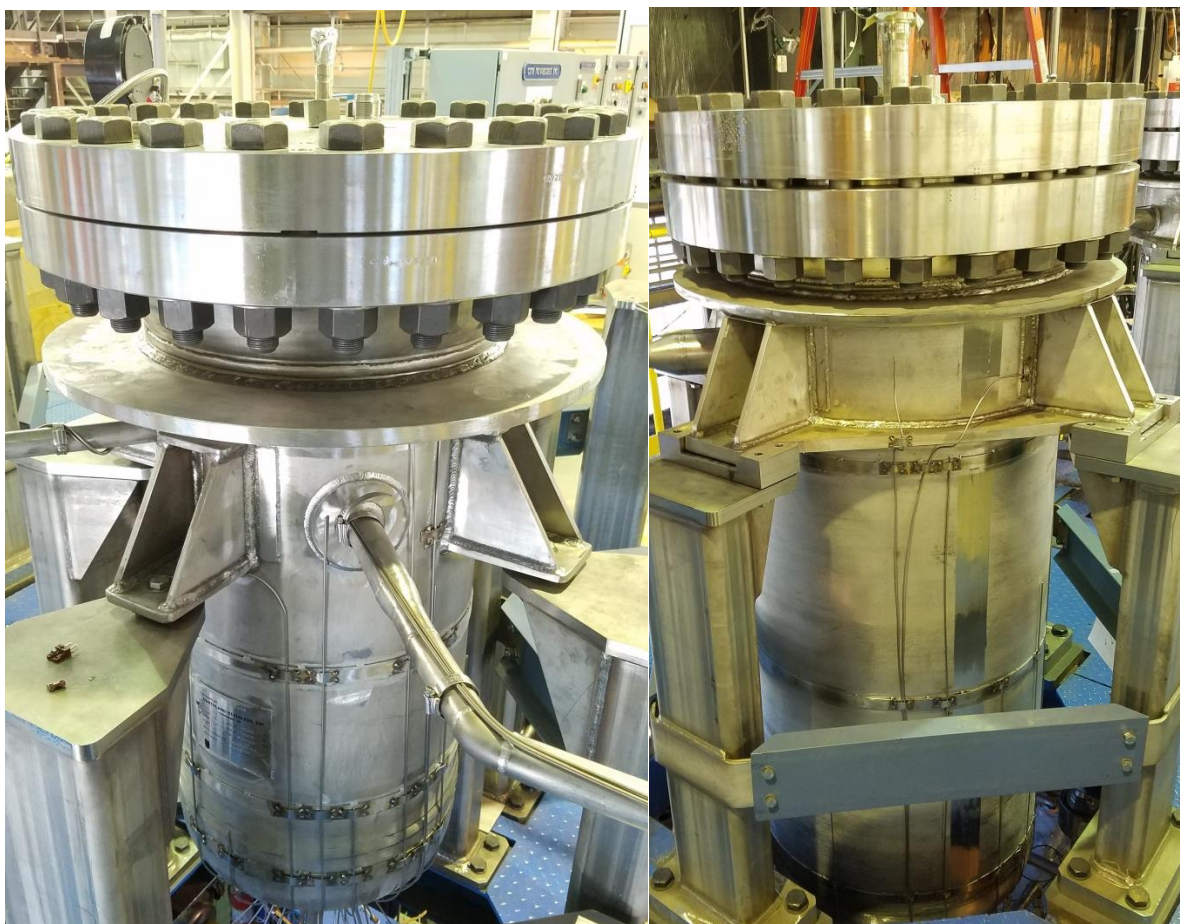
Figure 77 – 18" Test Vessel (left) and 28" Test Vessel (right) installed with thermocouples.

Each vessel has four individually controlled ceramic band heater zones (Figure 78). The vessels are then wrapped in removable insulation jackets with identical construction to previously discussed insulation jackets. Inverse to the plugging meter, the top of the test vessel is expected to need frequent removal and installation to access the flanges during test article insertion and removal. Therefore, the upper jackets are covered with a silicone raincoat and the lower jackets are housed with a more permanent stainless steel shroud as shown in Figure 79.

Figure 78 - 18" Test vessel with ceramic band heaters installed.

Figure 79 - 18" (left) and 28" (right) vessels covered with insulation.

3.2.8   *Expansion Tank*

The function of the expansion tank is to accommodate changes in liquid level that result from temperature changes in METL. The expansion tank was fabricated and delivered to Argonne during FY2014. During the spring of FY2015, the expansion tank was returned to Northland Stainless so that the nozzles could be reinforced to withstand the anticipated piping loads. Nozzle reinforcement has been completed and the expansion tank is now installed into METL (shown in Figure 80).

The body of the expansion tank is approximately 80" long, 8.7" in diameter, and is constructed of 304 stainless steel. It is about half full during normal operation which leaves enough gas space to accommodate changes in volume due to density changes caused by altering the sodium temperature. The sodium level of the loop is measured from within the expansion tank. A differential-pressure level sensor and an inductive level sensor are used to monitor the liquid level in the expansion tank which in turn, measures the sodium level in the test vessels as they are on the same elevation plane. Additional instrumentation can also be envisioned and inserted into the expansion tank via one of its connections.

Like the test vessels, cold trap, plugging meter, and dump tank; the expansion tank has thermocouples tack-welded to monitor and control the temperature (Figure 80). The expansion tank has thirty thermocouples and three control zones. Identical to the test vessels, ceramic band heaters are bolted together to surround the circumference of the expansion tank and this equipment is housed in an insulation jacket (Figure 81). Again, the jackets below the flange are covered in a stainless steel shroud and jackets on the flange are enclosed in a silicone raincoat for the same rationale described in the test vessel section.

Figure 80 – A photo of the expansion tank installed into the METL with thermocouples

Figure 81 - Expansion tank equipped with insulation jackets.

The original expansion tank flange had four VCR connections welded onto it. This allowed the expansion tank to be pressure tested with a flange but also provide the potential to be used in the future for instrumentation ports. The aforementioned VCR ports could not support the desired level instrumentation so a new expansion tank lid with two 1-1/2 Grayloc fittings with stems were welded onto a different flange and installed (Figure 82).

Figure 82 - New Expansion Tank Lid to Support Level Instrumentation

3.2.9   *Vessel Supports and Imitators*

During FY2015, the design, fabrication, and installation of the supports for the expansion tank, two 18" test vessels and two 28" test vessels was completed. The vessel support structures were designed by Argonne engineers to withstand a simultaneous fire and earthquake (850 [°F] / lateral 0.384 [g]).

As depicted in Figure 83, the different support structures connect directly to the mezzanine. Beneath the mezzanine deck plates, the support structures consist of horizontal beams welded into position, as shown in Figure 84. The vessels are attached to vertical stainless steel columns that are bolted to the horizontal supports (Figure 85).

Prior to the arrival of the vessels and to expedite the installation of the piping system, 'vessel imitators' were designed by Argonne engineers and fabricated by HR Slater. Figure 86 and Figure 87, show that the vessel imitators provided geometrically accurate mounting locations to support fabrication of the piping that connects to the expansion tank and four test vessels while these components were being constructed or having their nozzles reinforced. In summary, the use of these imitators allowed progress to be made in parallel with both the piping fabrication/installation and the vessel modifications required to accommodate the piping loads.
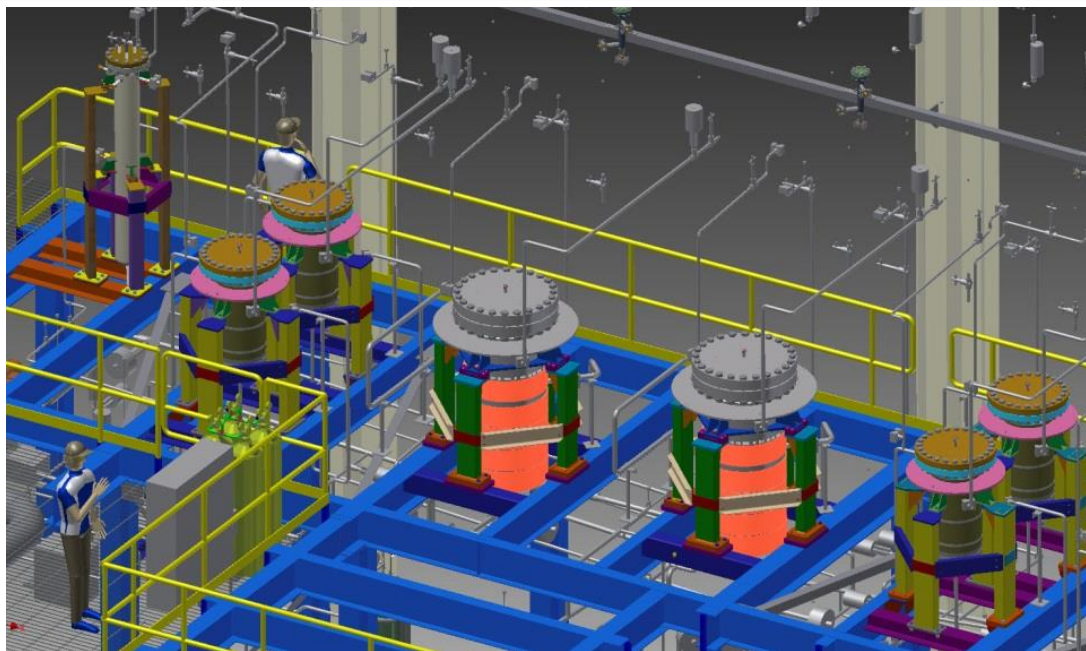
Figure 83 - A 3D model of the vessels and vessel supports.

Figure 84 - A photo of the 28" vessel support steel attached to the mezzanine structure.
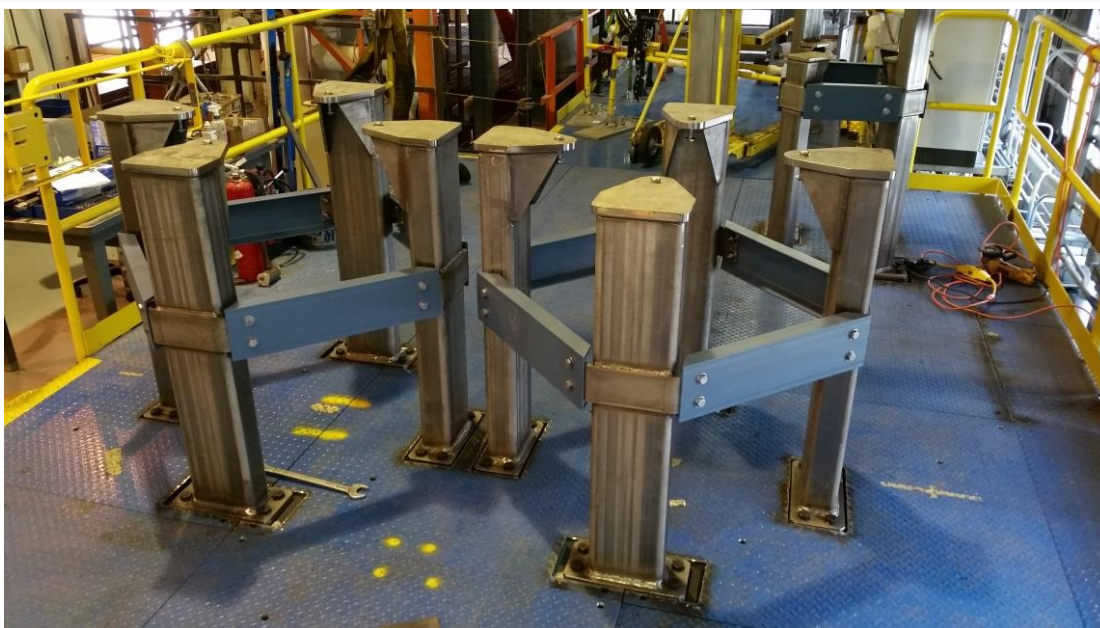
Figure 85 - A photo of the installed 18" vessel stainless vertical supports. (Holes to accommodate the vessel and piping have been cut in the mezzanine deck plates since this photo was taken.)
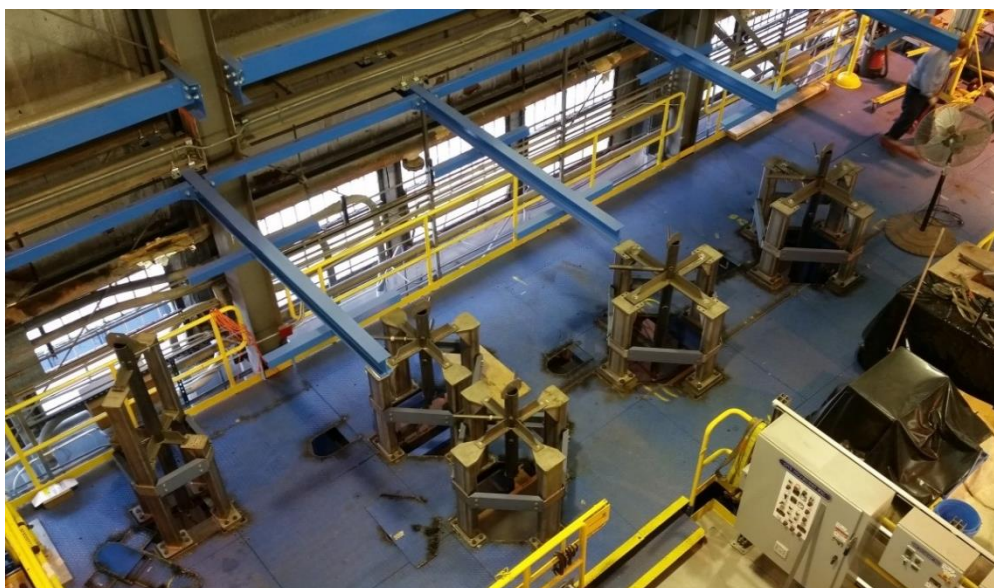
Figure 86 - An overhead photo of the METL mezzanine showing the installed vessel supports and vessel imitators required for Phase I.

Figure 87 - A photo of an 18" vessel imitator. The pipes extending radially from the imitator indicate where the nozzles on the actual vessel will terminate.

3.2.10 Inert Gas System

The METL facility uses argon cover-gas to maintain an inert environment above the liquid sodium. Cover-gas lines connect to the dump tank, expansion tank, each test vessel, and electro-pneumatic valves. The argon supply and distribution system is designed to:

- Purge and blanket the piping system, vessels, and tanks
- Maintain the required net positive suction head (NPSH) for the EM pumps
- Displace sodium from the system in order to achieve rapid draining
- Regulate and control the test loop pressure
- Inert equipment during removal and cleaning operations
- Actuate electro-pneumatic valves
- Bubble argon through a ΔP gauge dip tube.

The argon gas is supplied to METL from a 1000 [liter] Airgas 'micro-bulk' system located outside the Bldg. 308 high bay (Figure 88). This micro-bulk system contains high-purity liquid argon (< 1 [ppm] oxygen). On-line diagnostics within the tank provides the METL operators with real-time level measurement within the tank and automatically sends a refill request to Airgas whenever the liquid argon drops below 3/8ths full. The argon supply is also be able to provide 100 [psig] argon required to operate electro-pneumatically actuated valves.

Figure 88 - A photo of the installed 1000 [liter] microbulk system outside the Bldg. 308 hi-bay. The microbulk system was installed during FY2015.

METL has pressure relief valves designed to open in the event the METL system pressure exceeds 20 [psig] as the microbulk tank can reach pressures up to 500 [psig]. To further prevent the system pressure from reaching 20 [psig] an upstream regulator was installed. Additionally, the Swagelok valve actuators cannot experience pressures higher than 150 [psig]. Therefore, two parallel lines were installed from the argon 'microbulk' system, each with their own regulator (Figure 89). One regulator controls the system argon pressure (less than 50 [psig]) and another controls the valve actuator pressure (less than 150 [psig]).
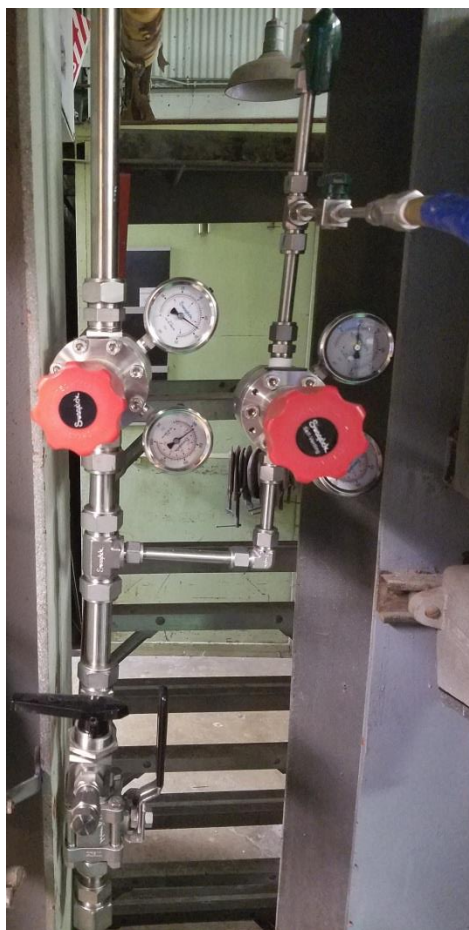
Figure 89 – Inter Gas System Regulators. Left regulator is for system pressure control and the right is for valve actuator pressure control.

3.2.11   Vent System

The vent system allows the METL operators to purge the system of argon gas to prevent over-pressurization. Venting operations are also required when the vessel is being filled with sodium and before the vessel flange is removed. Vapor traps are installed between the vessels and the vent tubing so that sodium vapor and/or aerosols are prevented from entering the unheated lines. A representation of the vent system that is attached to the expansion tank, dump tank, and each test vessel can be found in Figure 90.
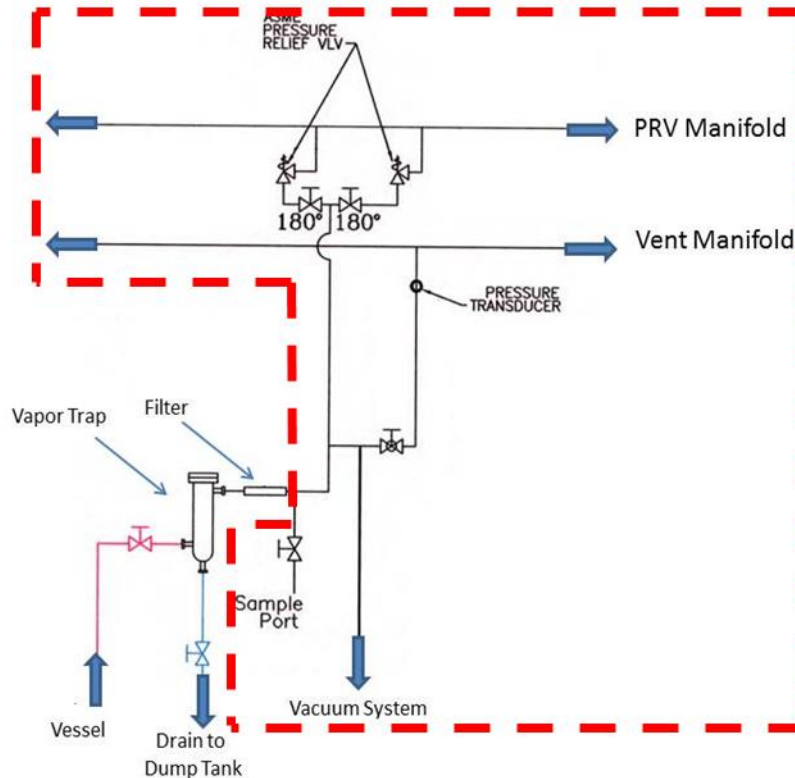
Figure 90 – A detail of the METL P&ID showing the vent system that is connected to the expansion tank, dump tank, and each test vessel. All components downstream of the vapor trap and filter are made of 0.065" wall thick seamless tubing since sodium corrosion is not a major concern (12).

Components inside of the dashed red line in Figure 90 are actually found on a separate sub-component of METL named, the downstream manifold. The downstream manifold is shown below in Figure 91; it houses sample port valves, pressure transducers, pressure relief valves, vacuum valves and relief selector "Toter" valves. The expansion tank, dump tank, test vessels and four future loops all have a set of the aforementioned equipment. The downstream manifold compactly and efficiently houses all of this equipment in one convenient location (western end of the mezzanine).

Figure 91 – Downstream Manifold. (Notice four future loops are not connected but rather welded shut until future expansion)

3.2.11.1   *Pressure Relief Valves*

Fourteen of the pressure relief valves (PRV) for Phase I of METL have been installed, as shown in Figure 92. The valves have a set-point of 20 [psig] and are capable of actuating at 1200 [°F] if needed. As illustrated in Figure 90, a pair of PRVs are connected to the expansion tank, dump tank and each test vessel. This configuration allows the METL operators to perform maintenance on one "Toter" PRV after transitioning the system to utilize the other. This process ensures that over-pressurization protection is never removed from a tank or vessel during maintenance.

Figure 92 - A photo of the pressure relief valves installed.

3.2.11.2 *Vapor Traps & Filters*

The filters, dump tank vapor trap and test vessel vapor traps required for Phase I have been fabricated and installed. Figure 93 shows that the support steel for the vapor traps are located above the mezzanine. This equipment was installed during FY2016.

Whenever cover-gas is vented from METL, sodium vapor and/or aerosols can be carried out of the system. To prevent sodium vapor from leaving the main system; vapor traps are installed in the inert gas vent lines of the expansion tank, dump tank, and each test vessel. The vapor traps have been designed to maintain a downstream concentration of sodium hydroxide at less than 1.15 [mg/m³] during steady-state operations. (See Figure 94 for the calculated sodium concentration at different cover-gas temperatures and pressures.)

The vapor traps are designed to continuously operate at ~120 [°C] so that the collected sodium vapor can be drained back into the system. In addition, sodium vapors easily solubilize in liquid sodium; therefore heating the vapor trap slightly above the melting point of sodium increases its effectiveness. Raschig rings serve as the random packing within the vapor trap and are shown in Figure 95. The Raschig rings have been inserted into the vapor traps along with stainless steel mesh for additional surface area.
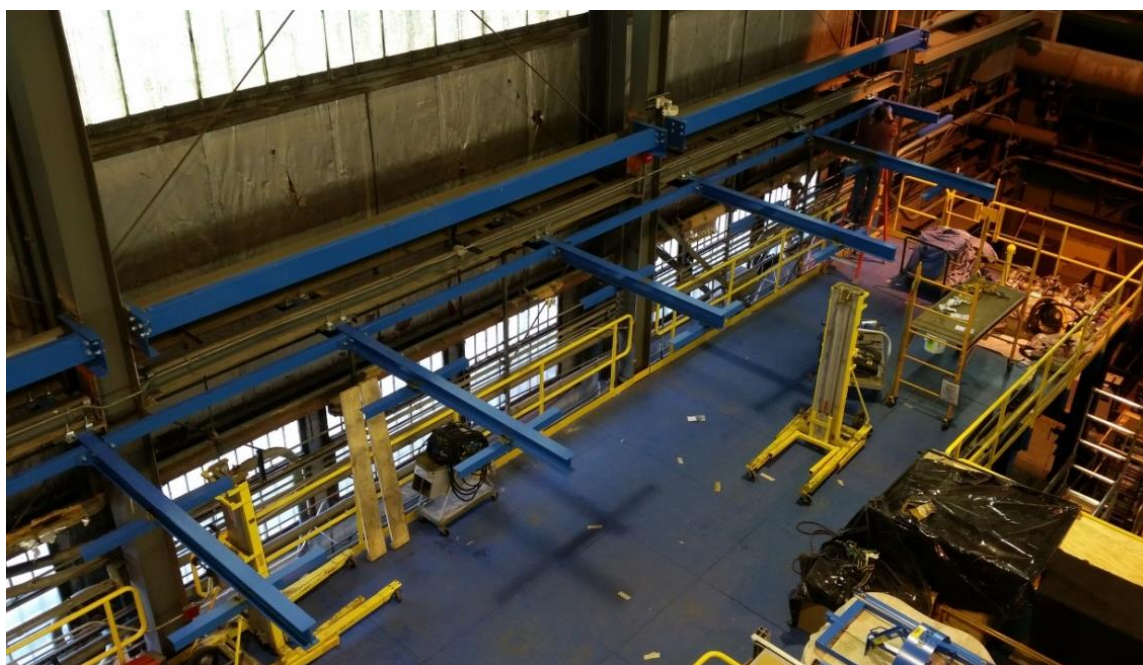
Figure 93 - A photo of the completed vapor trap supports and cantilever beams. The cantilever beams support the pipes connecting the vessels and vapor traps.

Temp [C]	Temp [K]		Argon Pressure [psig]					
			2	4	6	8	10	
100	373.15		1.42E-07	1.42E-07	1.42E-07	1.42E-07	1.42E-07	
125	398.15		1.08E-06	1.08E-06	1.08E-06	1.08E-06	1.08E-06	
150	423.15	Ideal vapor trap outlet ->	**6.45E-06**	**6.45E-06**	**6.45E-06**	**6.45E-06**	**6.45E-06**	
175	448.15		3.14E-05	3.14E-05	3.14E-05	3.14E-05	3.14E-05	
200	473.15		1.29E-04	1.29E-04	1.29E-04	1.29E-04	1.29E-04	
225	498.15	Acceptable vapor trap outlet ->	4.55E-04	4.55E-04	4.55E-04	4.55E-04	4.55E-04	
250	523.15		1.42E-03	1.42E-03	1.42E-03	1.42E-03	1.42E-03	
275	548.15		4.00E-03	4.00E-03	4.00E-03	4.00E-03	4.00E-03	
300	573.15		1.02E-02	1.02E-02	1.02E-02	1.02E-02	1.02E-02	
325	598.15		2.42E-02	2.41E-02	2.41E-02	2.41E-02	2.41E-02	
350	623.15		5.31E-02	5.31E-02	5.31E-02	5.31E-02	5.31E-02	
375	648.15		1.10E-01	1.10E-01	1.10E-01	1.10E-01	1.10E-01	
400	673.15		2.14E-01	2.14E-01	2.14E-01	2.14E-01	2.14E-01	
425	698.15		3.97E-01	3.97E-01	3.97E-01	3.97E-01	3.97E-01	
450	723.15		7.05E-01	7.05E-01	7.05E-01	7.05E-01	7.05E-01	
475	748.15		1.20E+00	1.20E+00	1.20E+00	1.20E+00	1.20E+00	
500	773.15		1.98E+00	1.98E+00	1.98E+00	1.98E+00	1.98E+00	
525	798.15		3.17E+00	3.17E+00	3.17E+00	3.16E+00	3.16E+00	
550	823.15		4.92E+00	4.92E+00	4.91E+00	4.91E+00	4.90E+00	
575	848.15		7.46E+00	7.44E+00	7.43E+00	7.42E+00	7.41E+00	
600	873.15		1.11E+01	1.10E+01	1.10E+01	1.10E+01	1.10E+01	

Right-side vertical label: [g Na / m^3] (Green = Acceptable / Red = Unacceptable)

Figure 94 - This table shows the calculated concentration [g/m³] of sodium in argon as a function of temperature and pressure. 1.15 [mg] of sodium per every 1 [m³] of argon is considered to be acceptable. These numbers were calculated using (6).

Figure 95 – A photo of ¼" x ¼" Raschig rings that increase the surface area within the vapor traps.

Dump Tank Vapor Trap (DTVT)

During an emergency drain, up to 800 [gal] of sodium could be driven back into the dump tank within 15 [min] utilizing argon gas pressure. Accordingly, the DTVT must be able to remove the sodium vapor and/or aerosols from the argon that is displaced out of the dump tank by the draining sodium. As shown in Figure 96, the DTVT has a blower fan that provides the active heat removal to handle emergency drain conditions. The air is ducted along the length of the vapor trap (between the outside of the vapor trap and the radiant band-heaters). Ducted air and radiant band-heaters are used to maintain the operating temperature of the device. The DTVT was designed by Argonne and then fabricated/tested by a local vendor during FY2015. The DTVT is currently installed as shown in Figure 97.

64.2"
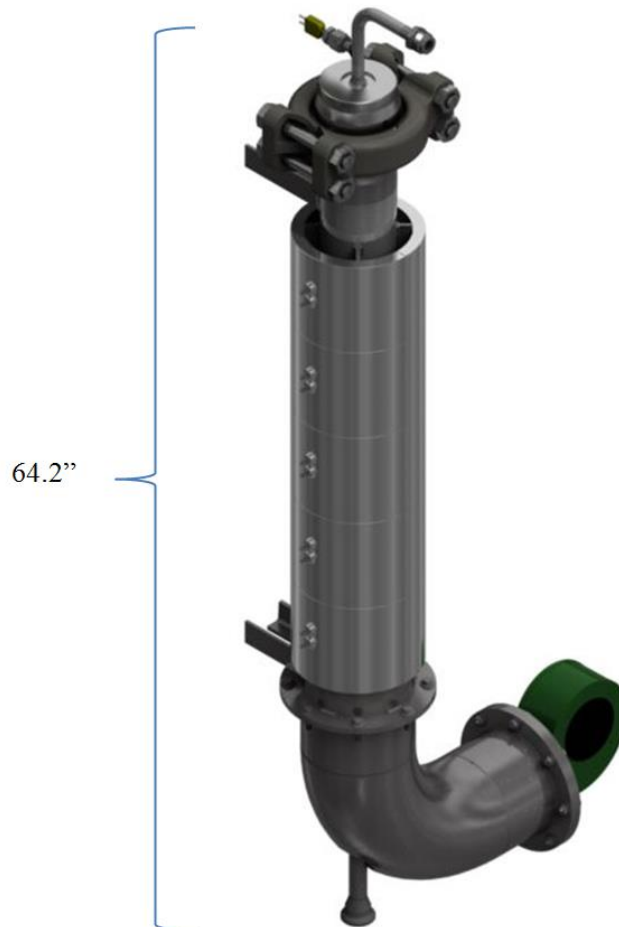
Figure 96 – A 3D model of the dump tank vapor trap.
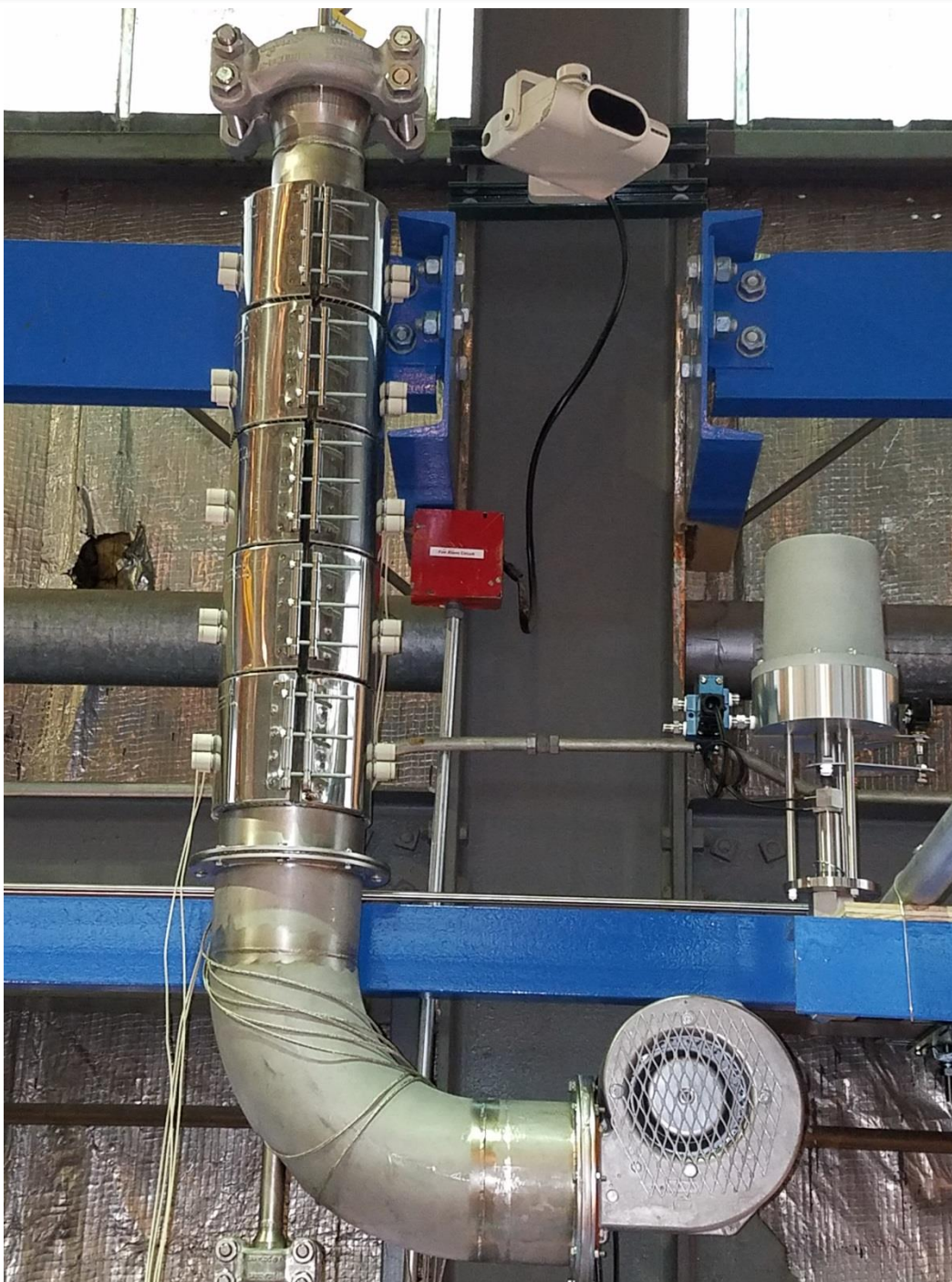
Figure 97 - A photo of the completed dump tank vapor trap during an inspection at Meyer Tool & Mfg.

Vessel Vapor Traps (VVT's)

Unlike the DTVT, the VVT's do not have an active cooling system since they are not used during emergency drains. The VVT's have been designed to have the same overall dimensions as the DTVT to enable interchangeability during operation and so that a common support design can be used for all vapor traps.

Originally, spiral-wound "shoe-string" cable heaters were to be used to maintain the vessel vapor traps at ~120 [°C]. Testing and analysis performed with a thermal imaging camera indicated that the required pitch for the "shoe-string" cable is roughly the diameter of the vapor trap (see Figure 99). All five of the VVT's required for Phase I have already been fabricated, tested, and installed by ANL-CS.

In FY2018, the heaters for the vapor traps were changed from cable heaters to ceramic band heaters after the initial heatup testing of METL.

Figure 98 – A single VVT (left) and the remaining VVTs (right).
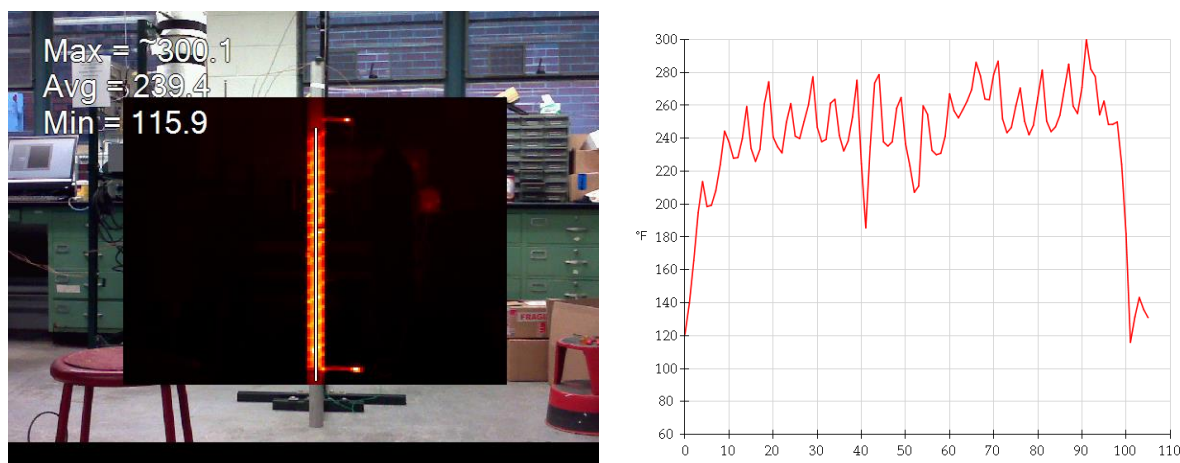
Figure 99 – Left: An infrared image of the small vapor trap heater test using a coiled MI heater cable. Right: The temperature profile along the outside of the smaller vapor trap as measured with the infrared camera.

3.2.11.2.1   Filters

Filters are installed downstream of each vapor trap. The filters, depicted in Figure 100, are designed to capture sodium aerosols that were not contained by the vapor traps. Each filter houses a finned tubing element to provide additional surface area for aerosols to adhere to, as shown in Figure 101. The additional holes in the finned tube element help to ensure that the unheated filters will not clog during operation, even if the finned section becomes completely filled with solid sodium. All six filters required for Phase I have been fabricated, radiographed, pressure tested and installed by ANL-CS. Figure 102 provides a photo of the filters installed at the outlet of the vapor trap.
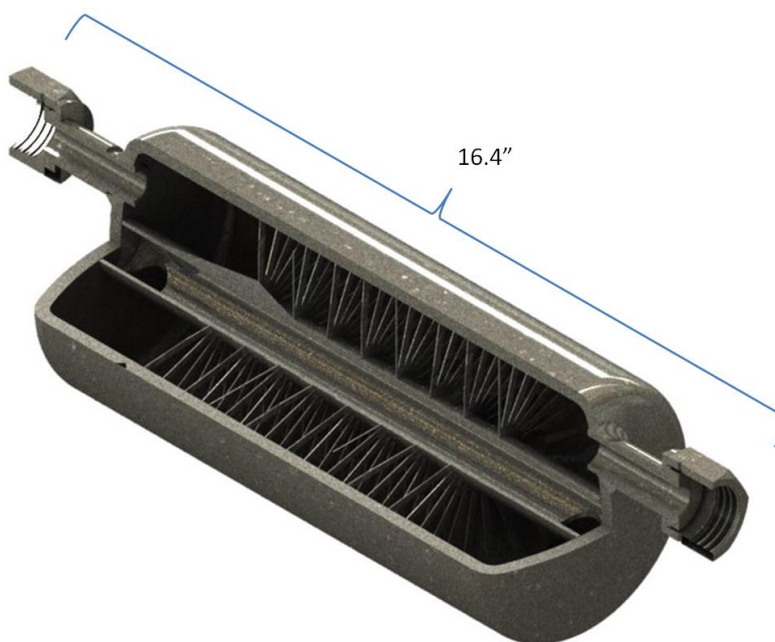
Figure 100 – A 3D model of the filter assembly. The finned tubing element provides surface area for the accumulation of sodium aerosols.
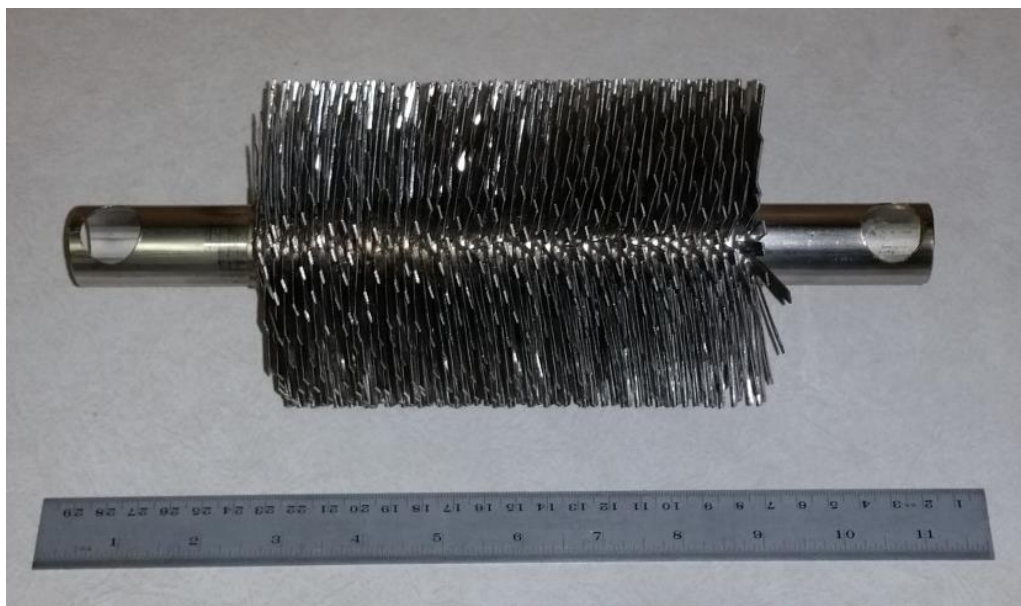
Figure 101 – A photo of the finned tubing element. The additional holes on the ends of the tube ensure that the filter cannot become clogged during operation.
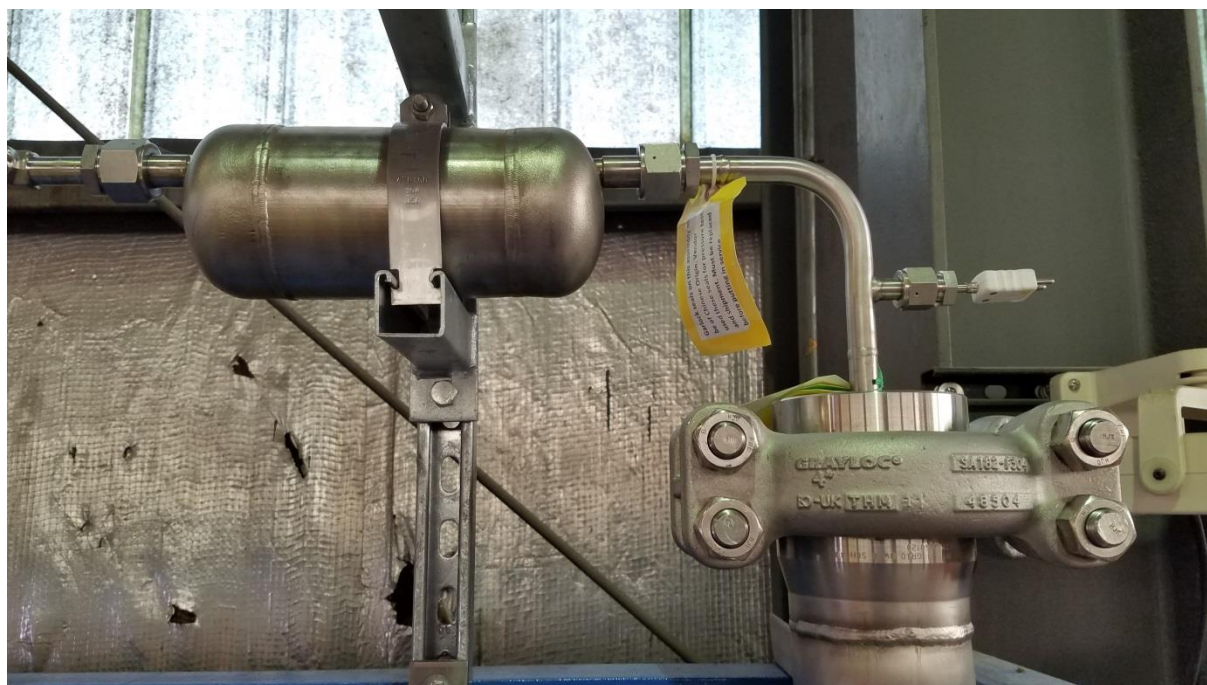
Figure 102 - A photo of the six completed filters required for Phase I.

3.2.11.3   *Vacuum Pumps*

A roughing vacuum pump (Figure 103) was purchased for helium leak testing and the initial cleaning and "bake-out" of METL as well as filling the piping and vessels with sodium. The vacuum pump is a dry scroll pump with a capacity of 500 l/min and can reach an ultimate

pressure of 9.3E-3mbar. A turbo pump can be configured downstream of the roughing pump that may reach lower absolute pressures but is unlikely due to the size of the connection, multiple piping bends and conductance of METL. Therefore, the tentative plan is to solely rely on the roughing vacuum pump which also ensures no sodium distillation occurs as the current vacuum pump cannot reach these absolute pressures.

Figure 103. Roughing Vacuum Pump

The vacuum pump is connected to a vacuum manifold (Figure 104) and the vacuum manifold is connected to the downstream manifold. This allows the vacuum pump to be connected to individual vessels or the entire volume of METL. The vacuum manifold consists of four valves. Two of the valves are metering valves with a Vernier scale and the other two are welded bellows seal valves. Piping these three valves in parallel allows for precise control when pulling a vacuum on one or multiple vessels. Lastly, the fourth valve in series is an isolation valve to prevent a vacuum from being accidentally being pulled on METL.

Figure 104. Vacuum manifold

3.2.12   *Electromagnetic Pumps & Flowmeters*

All of the electromagnetic (EM) pumps, flowmeters and their control systems have been installed and have been electrified. The primary, purification and diagnostic loops all have their own individual EM pump and flow meter. All of the EM pumps and flowmeters were provided by an outside vendor.

3.2.12.1   *Electromagnetic Pumps*

An annular linear induction pump (ALIP) (Model: LA-125, see Figure 105) is used to push sodium through the main loop and test vessels. Two AC conduction pumps (Model: CA-15, see Figure 106) control the flow of sodium through the plugging meter loop and the cold trap loop. The ALIP is connected to the main loop using 1-1/2" Grayloc fittings while the two conduction pumps are butt-welded to the ¾" piping in the purification system.

Frozen sodium within the main EM pump can be melted using the built-in preheating mode, which is equivalent to 20% pump power. This custom preheat mode quickly cycles the VFD between forward and reverse in order to generate heat within the pump without exerting a net force on the sodium. Once the sodium within the pump is liquid, the pump operates by changing the settings on a variable frequency drive. For long term experiments, a constant operating condition can be maintained by using the vendor's flow meter and associated control system.

Coil temperature of the ALIP is an important parameter that must be routinely monitored in order to preserve the coil integrity and ensure pump longevity. The pump power supply has an

automatic feature that turns the pump off if thermocouples embedded within the pump body exceed a certain temperature. Additionally, forced air cooling is also provided to the ALIP to help maintain low coil temperatures. Due to the reliability concern when using cooling fans, a safety feature was added to the control system to monitor cooling fan operation. A current transducer monitors the amperage draw for the cooling fans, and if a change is detected (as when a fan stops operating), a warning light is illuminated.

Figure 105 – A photo of the annular linear induction pump (ALIP) that is installed in the main loop.
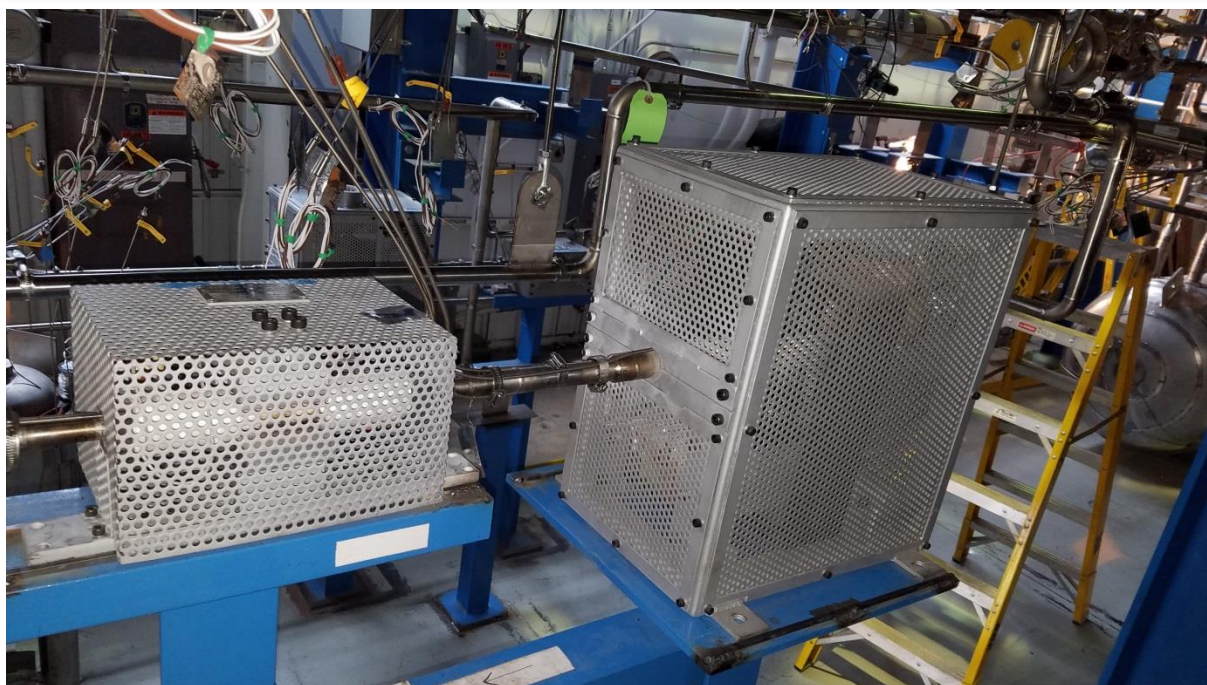
Figure 106 – A photo of a conduction pump (CA-15, right) and EM flow meter (left) that are installed in the diagnostic (plugging meter) loop. The diagnostic and purification loop utilize identical EM pumps and flowmeters.

Specifications of the LA-125:

Mechanical:

- Dimensions: L = 637 [mm], D ≤ 425 [mm]

- Weight: M ≤ 80 [kg]

- Installation: Orientation only affects drainage, not performance.

- Connections: 1.5" Schedule 40 pipe Grayloc hub

- P_{Max}:   6 [bar] / 90 [psid Δ]

Thermal:

- Cooling: Max ambient temperature = 55 [°C]

                Coil temperature should be kept at ≤ 220 [°C].

                External fans are built into the design.

- Heating: Resistive heaters can preheat pump to 300 [°F] / 149 [°C]

                Power supply provides 3-phase power to drive the induction pump and single-phase to power the trace heater.

Electrical:

- Power Supply: 480 [VAC] / 60 [Hz] / 3-phase

Control methods:

- A variable frequency drive (VFD) is be used to power the pump. The control resolution of the VFD is expected to be < 1%. During normal operation, the flow rate is measured using the flowmeters provided by the vendor.

Flow:

- The pump can have reverse flow operation. The max flow rate is 10 [gpm]. The pump NPSH is 0.7 [bar-abs] / 10.2 [psia].

Specifications of the CA-15:

Mechanical:

- Dimensions: L = 650 [mm], D = 398 [mm], H = 506 [mm]

- Weight: M = 88 [kg]

- Installation: Orientation only affects drainage, not performance.

- Connections: Butt-welded connection

- P_{Max}:   6 [bar] / 90 [psi Δ]

Thermal:

- Cooling: Maximum ambient temperature 55 [°C]

                    No forced air cooling required / Current limited to ~ 25 [A]

- Heating: Resistive heaters can preheat pump to 300 [°F] / 149 [°C]

Electrical:

- Power Supply: 240 [VAC] / 60 [Hz] / single-phase.

Flow:

- The pump can have reverse flow operation. The max flow is 2 [gpm].

3.2.12.2   *Electromagnetic Flowmeters*

Two different types of electromagnetic (EM) flowmeters are used in METL. One of the flow meters (shown in Figure 107), monitors the flow through the main loop while the other two (shown in Figure 108) monitor flow through the cold trap and plugging meter. Each of the three flowmeters can be coupled to the power supply of the corresponding EM pump to precisely control the sodium flow rate.

The flowmeter for the main EM pump has a 1-1/2" Grayloc hub on each end. And flowmeters in the purification/diagnostic system are butt-welded into the 0.75" Sch. 40 piping system.

Flowmeter Requirements:

All flowmeters are rated for minimum of 0°F and maximum of 1112 [°F] / 600 [°C] at a pressure range of 1×10^{-4} Torr (vacuum) to 218 [psig].

Flowmeter in the main loop:

- Flow rate of 10 [gpm] +10% / -0% at pressure of 5 [psid Δ]

- ±2% of the full scale value at 300 [°C]

Flowmeters in the purification system:

- Flow rate of 2 [gpm] +10% / -0% at pressure of 3 [psid Δ]

- ±3.5% of the full scale value at 300 [°C]
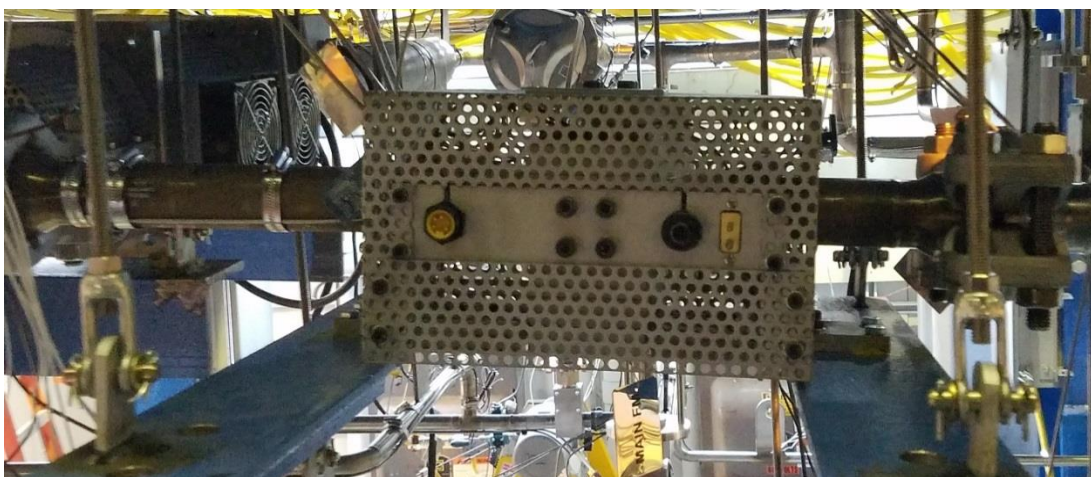
Figure 107 – Installation of the flow meter for the primary loop.

Figure 108 - Picture of the purification (cold trap) loops' pump (left) and flow meter (right).

3.2.12.3   *Pump & Flowmeter Control Panels*

Each pump and flowmeter has a dedicated control panel. As shown in Figure 109, the controls for all the pumps and flowmeters were installed during FY2014. Bucking transformers and variable speed drives for the AC conduction pumps were installed in FY2017.

The right column of enclosures from top to bottom consists of: a EM flow meter power supply and display, motorized variac, and EM pump power supply and controls. These enclosures are for the plugging meter and the adjacent column of enclosures are for the cold trap EM pump and flow meter. The far left is the variable frequency drive enclosure for the main loop EM pump. The middle left column of enclosures contains the main flow meter panel and below it are two bucking transformers. The bucking transformers limit the amount of power that can be delivered to the conduction EM pumps found on the cold trap and plugging meter loops.

Figure 109 – Control panels for the EM pumps and flowmeters.

3.2.13   ***Data Acquisition & Control System***

During FY2015, the design of the METL piping system was completed. Using the finalized models and piping isometrics, Argonne engineers were able to determine the exact quantity and power requirements of all the Phase I heater zones. A scalable, industrial hardware system was designed and fabricated by Eurotherm. This hardware controls all of the heaters, valves and other components that are installed in METL.

As listed in Table 5, the primary components for Phase I are all CAT6 Ethernet enabled, so a local Ethernet network serves as the backbone for data transfer. CAT6 was selected for its high speed data transfer capability, up to 1,000 [Mbit/s], which provides a long term foundation for operator control and data acquisition.

Table 5 – An overview of the primary communications devices for Phase-I METL

Device	Description
Eurotherm Cabinet	Houses Mini8s and 240VAC heater zone disconnects
Mini8	PID temperature control for heater zones TC monitoring of heater zones Digital on/off logic for gate valves
PenGUIN display	Firmware based monitoring of Mini8
Analog display	Direct read-out of analogue flow, ΔP, etc., signals
Nat. Instr. cDAQ	Data acquisition of research-related analogue inputs (TC's, flow meters, ΔP, etc), analogue outputs (misc. control valves)
CAT6 hardware	DHCP server and link for CAT6
Central computer	Central access point for viewing, controlling, and logging of entire device suite via LabVIEW

3.2.13.1   *Multi-Device Integration*

Software communications and primary operator display are built around LabVIEW, a development environment from National Instruments (NI) geared specifically towards data acquisition and experimentation. LabVIEW is installed on the central control computer in order to provide access to the National Instruments and Eurotherm systems. The combination of these platforms create a framework for controlling METL components and logging data.

Due to mission critical demands for safety, functionality and facility up-time; the data acquisition and control system features both redundant and firmware based systems, as depicted in Figure 111. For example, if a software glitch occurs, the METL operator is still be able to control critical systems via the PenGUIN display. Similarly, in the event of a total display failure, the autonomous Mini8's continue to operate at their specified set points.

Logging of all these devices, including their user-defined set points, temperature read-outs, and valve position states, is be performed via LabVIEW software and written to the disk in regular intervals. These log files are first be stored primarily on the local disk, which has been configured in a RAID1 for redundancy. Should any single hard drive fail, the system will continue to operate without interruption or loss of data.

The data is backed up in an ANL-NE server which is currently configured for 16TB of data but has the ability to expand to an impressive 1PB. The server has capacity for sixty-four hard drives and can operate with the loss of ten drives. ANL-NE has a contract with the manufacturer for 24/7 support so that if a drive does fail it can be corrected/replaced within twenty-four hours. An example of the METL communications network is provided below in Figure 111.

Figure 110. ANL-NE Data Storage Server with UPS backup.
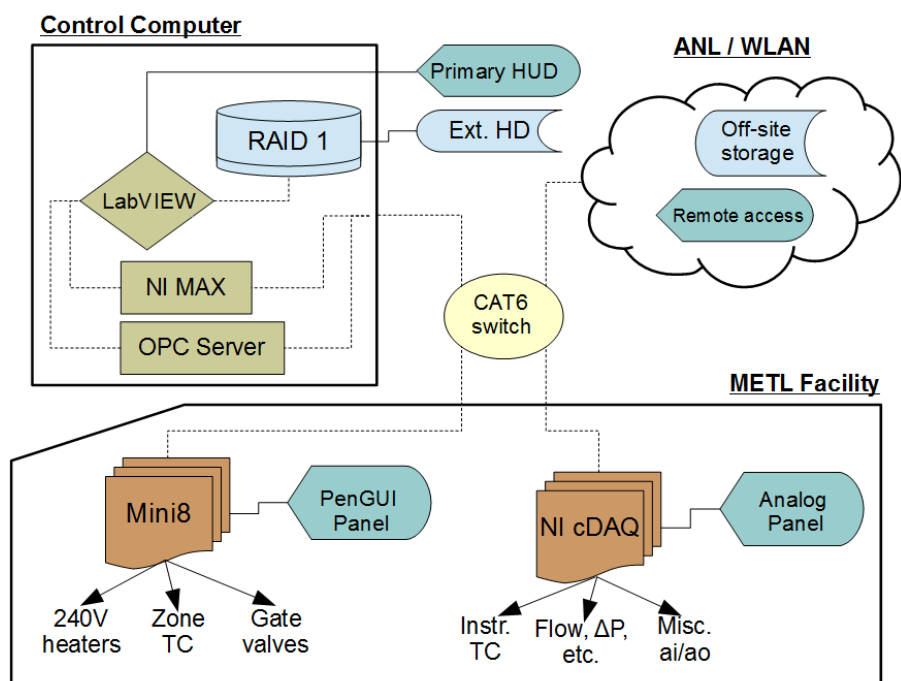
Figure 111 – Proposed communications network to be used for METL (13).

3.2.13.2   *Eurotherm Enclosures*

After several internal safety review meetings, Argonne engineers have opted to use hardware to provide ground-fault protection of equipment (GFPE). Illustrated in Figure 112, a simplified wiring diagram below; every heater circuit in the system is monitored by GFPE hardware with an adjustable set point. Implementing this hardware ensures that the METL power systems comply with NFPA 70-2014.

Additionally, solid state relay (SSR) failure was identified as the most likely type of fault in the power control system. Argonne engineers have decided to use 'intelligent' or shunt-enabled breakers in each heater zone to provide added protection against runaway heaters should an SSR fail in the 'closed' position. Argonne engineers worked closely with Eurotherm to determine the appropriate power and control layout for Phase I of METL. All of the power and control enclosures were created, delivered, and installed in building 308. Also, the Eurotherm enclosures have been electrified and commissioned.
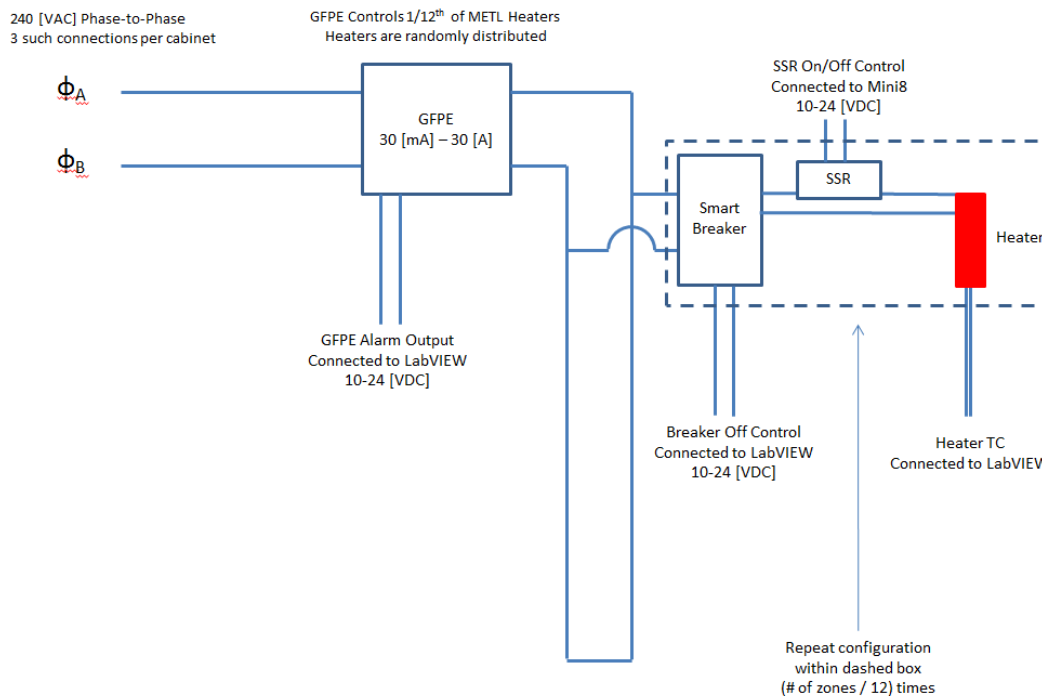
Figure 112 - An illustration showing the METL heater control circuit design (13).

There are a total of five Eurotherm enclosures. One of the enclosures is a control enclosure (CE1) and is shown below in Figure 113. CE1 has twenty-two Mini-8 Eurotherm controllers which communicate over Ethernet via TCP/IP MODBUS with LabVIEW. Each controller is capable of processing sixteen heater PID loops with thirty-two type K thermocouple inputs. The Mini-8 calculates PID percentage based on the set point, present value, and user-defined proportional gain, integral and high/low cutback parameters.

Then, the Mini-8s communicate its' percentage to T2750 controllers located in the power enclosures (discussed subsequently) to physically close or open a circuit to its' respective

heater. The duration each circuit is closed is proportional to the percentage value received from a Mini-8. As previously discussed, in the event a host computer or display panel fails; the Mini-8's have their own real-time microprocessor so they continue to operate at their last specified condition. However, there is a watchdog in place that monitors network traffic between CE1 and the power enclosures to automatically open heater circuits if communication with the Mini-8's is lost.

Figure 113 – Control Enclosure (CE1).

Type K thermocouples are accurate, repeatable, inexpensive and readily available. However, their relationship to temperature is a function of millivolts (mV) of electrical potential. To ensure the integrity of the signal and protect it from electromagnetic interference; twenty-one thermocouple umbilical enclosures (Figure 114) were installed throughout the METL footprint. These enclosures have forty-eight screw terminals to connect twenty-four individual type K thermocouples. An umbilical is connected to all of these terminals with type K thermocouple twisted pair wire which is surrounded by a shield, grounding "drain" wire and insulation. These umbilical cords are routed and connected to a mini-8 controller inside CE1 on the mezzanine. The distance from an enclosure to a mini-8 varies but can be upwards of 80 feet.
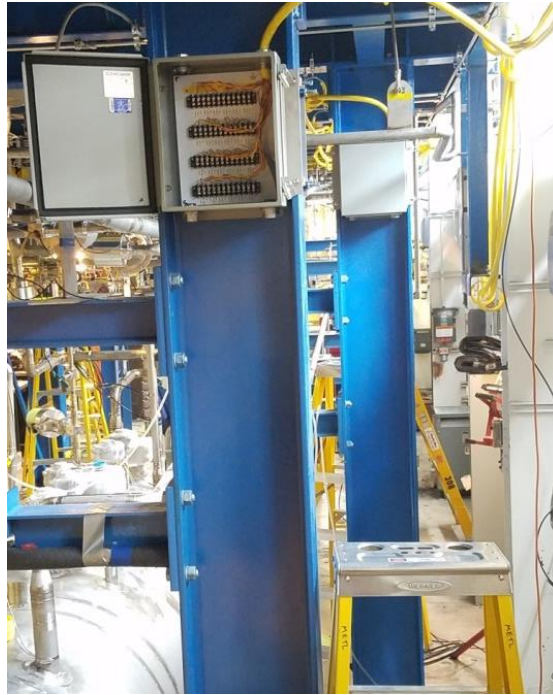
Figure 114 – Thermocouple Umbilical Enclosure.

There are a total of four power enclosures (PE1 through PE4). PE1 and PE2 house the hardware responsible for controlling higher currents such as ceramic band heaters for the test vessels, dump tank and expansion tank. PE3 and PE4 contain hardware that controls the heater zones for the valves and piping system which draw far less current. The power enclosures are located northwest of the mezzanine in Building 308 as shown in Figure 115.

Figure 115 – (Front to Back) Power Enclosures 4, 3, and1-2. PE1 and PE2 are located in the same rear column with PE 2 on the left. (Roof penetrations are for air conditioning units)

All power enclosures are analogous with respect to the equipment they contain such as; circuit breakers, distribution blocks, solid state relays (SSRs), miniature circuit breakers, Foxboro T2750 programmable automation controller(s), 24VDC power supplies and shunt trips. All of this equipment is wired together and neatly routed through wire ducts. This equipment can be seen below in Figure 116. Power is supplied from Building 308's electrical yard to the PEs and is distributed throughout METL via 14" X 14" wire trough. In summary, the functions of the power enclosures are:

- Utilize 24VDC power supplies to provide excitation for the T2750s.
- T2750 receives a signal from a Mini-8 to close or open the contact on an SSR by delivering or withholding a 24VDC signal
- A circuit breaker closes its' contacts automatically in the event the equipment draws excessive amounts of current.
- If the SSR fails closed (run away SSR), a T2750 outputs a 24VDC signal to activate the shunt which then forces the aforementioned breaker open.
- There are ground fault protection of equipment (GFPE) interrupters which open the circuit if current leakage is present.
- PE3 contains a T2750 that directly actuates all of the valves found in METL.

Figure 116 – Hardware found in PE1, 2, 3, and 4. DC power supplies and T2750s are located on the left and circuit breakers, shunts, and SSRs are shown to the right

3.2.13.3   PenGUIN Display Panel

Installed on the exterior of CE1 is a standalone display panel that provides communication with the Mini8 controllers. This panel, while primarily an industrial device for routine monitoring; provides a redundant, robust and fully standalone means to view the condition of METL in the event of any computer crashes. An example page for the human-machine-interface (HMI) is shown below in Figure 117.

Figure 117 - A photo of the PenGUIN display panel.

3.2.13.4   METL Control Room & iTools / LabVIEW Programming

During FY2015, the control computer and flat-screen displays were installed into the refurbished METL control room (Figure 118). Control room development continues as METL will operate 24/7. The controllers discussed in section 3.2.13.2 are suitable for operating heaters and valves as their data sampling and response time does not have to be rapid. However, METL has components and operations that will require faster performance; possibly to the level of kHz. Therefore, those applications are managed with National Instruments (NI) hardware which has the ability to sample at frequencies of Mhz.

Figure 118 - A photo from within the METL control room. The control room was refurbished during FY2015 and work transitioning it to a 24/7 operation center continues.

A variety of NI hardware was purchased to accommodate the different types of digital, analog, and thermocouple signals that are used in METL. A photo of a typical NI chassis can be seen in Figure 119. Eight of these devices have been installed along the METL mezzanine to provide control, data acquisition and flexibility for future experiments. A NI power supply and distribution block (Figure 119, right) provides the NI chassis with excitation. All National Instruments hardware has been installed and commissioned.

Eurotherm controllers have their own software to program their logic as does NI hardware. NI hardware uses LabVIEW software to program their logic. LabVIEW is also used to write programs to interface with Eurotherm controller logic.
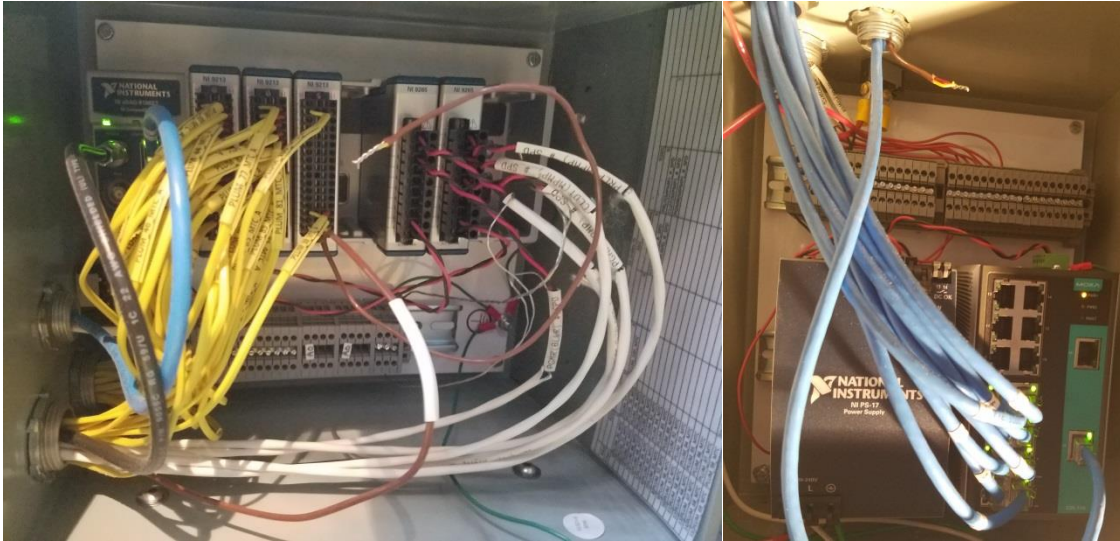
Figure 119 - A photo of an NI c-DAQ 9188, 8 module chassis (left) and NI power supply (right).

LabVIEW is capable of communicating directly with the Mini8 via an OPC server or MODBUS, which ultimately provides a convenient point for running and logging experiments in METL. The Mini8s feature a hardware flash memory that stores a "recipe", or programming logic that controls the operation of the device and its individual channels. Using a block-diagram system for programming, users are able to route wires to each of the Mini8's parameters and create such schemes as PID heater controls, safety limit trip points, or valve logic. An example block diagram for Heater Zone #4, on the Mini8-1, is shown below in Figure 120.
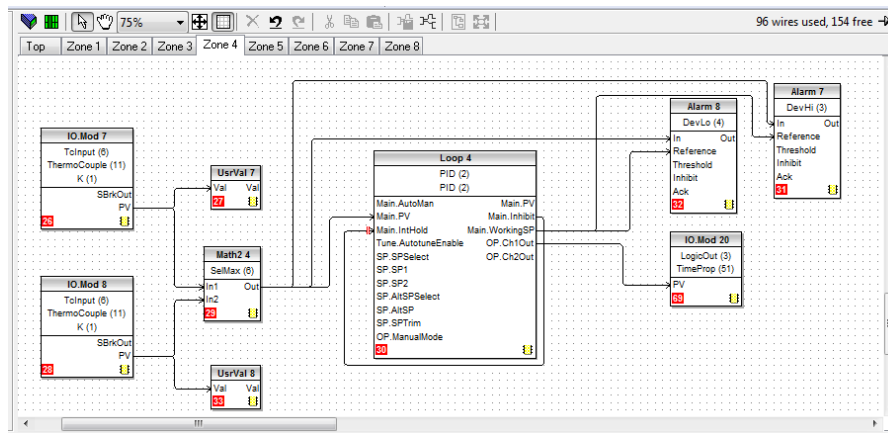
Figure 120 - An example of an iTools recipe, Mini8-1 PID loop

The development of the LabVIEW system is nearing completion and current efforts are focused on ensuring METL can reliably operate autonomously, send emergency notifications and operate the building 308 scrubber. This style of programming, while similar to the iTools block scheme, is more complex but significantly more powerful. The graphical user interface of the program which the METL operator uses is shown below in Figure 121.
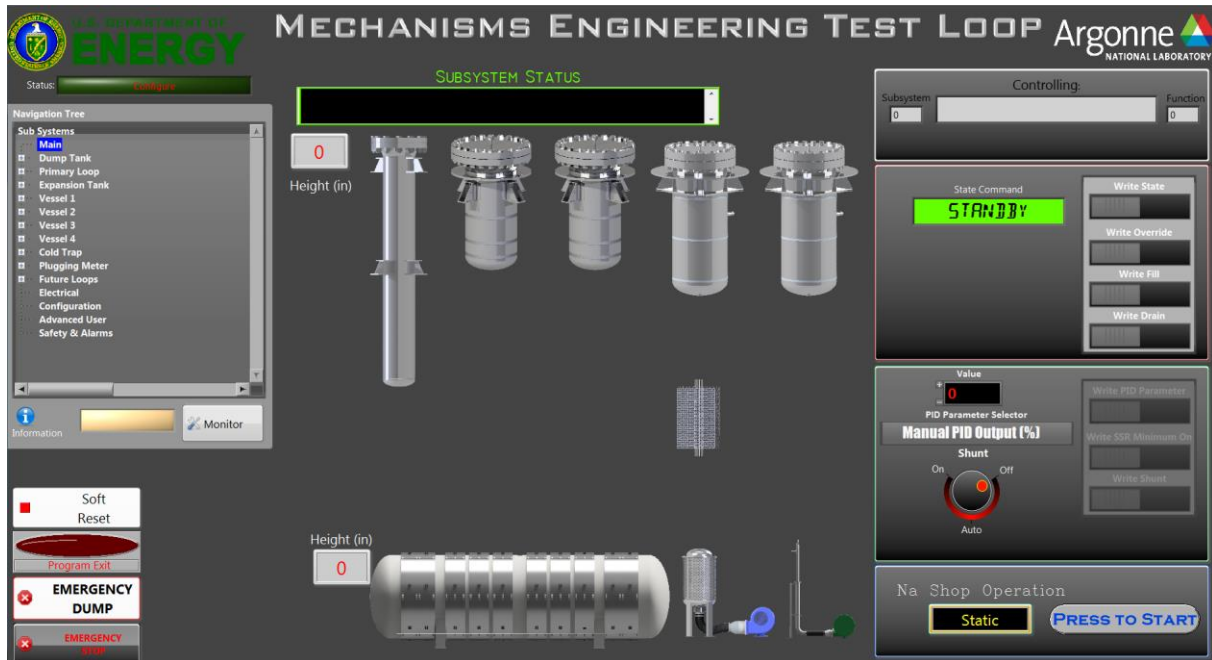
Figure 121 - METL GUI

3.2.14   *Instrumentation*

METL cannot only be envisioned as a facility for multiple experiments, but also as an experimental apparatus itself. Therefore, instrumentation is required not only for proper and safe operation but for measuring the performance of its components. Instrumentation for Phase I includes pressure transducers, thermocouples, inductive level sensors, differential pressure sensors and volumetric flow meters/controllers.

3.2.14.1   *Pressure Transducers*

Argonne engineers initially worked with an outside vendor to produce a prototype NaK-filled transducer that could be used in METL (Figure 122). This sensor model is typically used in the high-pressure plastic extrusion industry but the sensor body, diaphragm, and Grayloc fittings shown in Figure 123 are all made from Inconel-718 so it could also be used in high temperature sodium systems.

Concerns over the accuracy and sensitivity of the Gefran hardware prompted Argonne engineers to initiate discussions with another vendor regarding custom NaK-filled pressure transducers for the differential pressure (DP) gauge. Thus far, Argonne has ordered fourteen single-point pressure sensors from the second vendor for use within METL. These fourteen sensors are connected to the system using Grayloc fittings, as shown in Figure 124. All fourteen pressure sensors have arrived at Argonne and twelve have been installed (remaining two are spares). An example of the pressure transducer is shown in Figure 125.
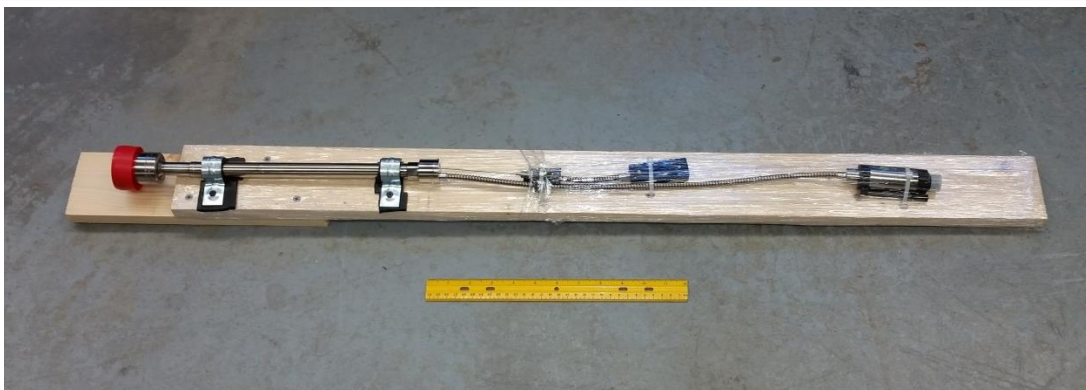
Figure 122 – A photo of the NaK-filled pressure transducer that has been delivered to ANL. The transducer can connect to the METL piping system using a Grayloc hub.

Figure 123 – A close-up photo of the diaphragm of the transducer. The diaphragm is ~ ½" in diameter. This small diameter is not expected to provide the adequate sensitivity that is required for the METL level control system.
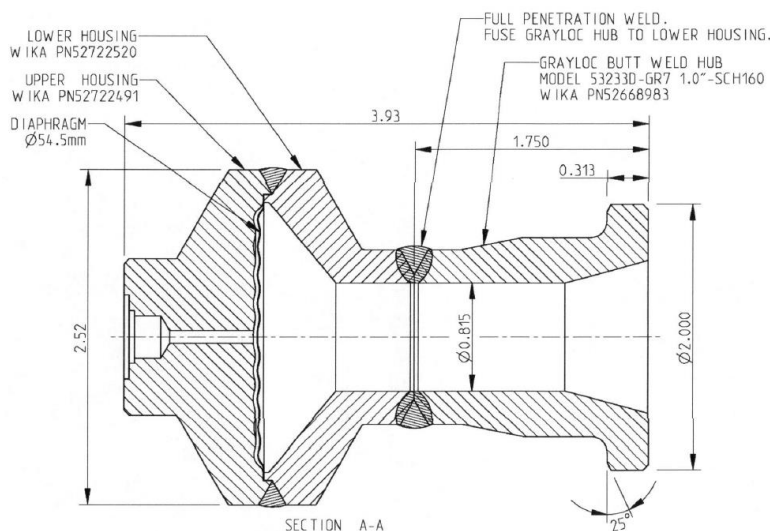
Figure 124 - A drawing of the single-point NaK-filled pressure transducers that will connect to the METL system using Grayloc fittings. This sensor is rated for 200 [psig] at 1200 [°F] (12).

Figure 125 – Yokogawa pressure transmitter with a NaK filled capillary connected to a WIKA pressure diaphragm seal with a welded Grayloc connection.

Grayloc connections are made with a seal between two hubs and a two-piece collar which clamps them together. The collar has four bolts that must be tightened to the correct torque specification. These Grayloc fittings are expected to experience temperatures similar to the loops they are installed on and therefore thermal expansion of the bolts from the increase in temperature will result in the bolts traveling outside of their torque specification. The Grayloc fittings were equipped with insulation jackets and raincoats identical to the systems valves so that the insulation can be easily removed, bolts torqued to specification, and quickly installed.

A pressure transducer which is connected to METL via Grayloc connection is insulated with a jacket below in Figure 126.
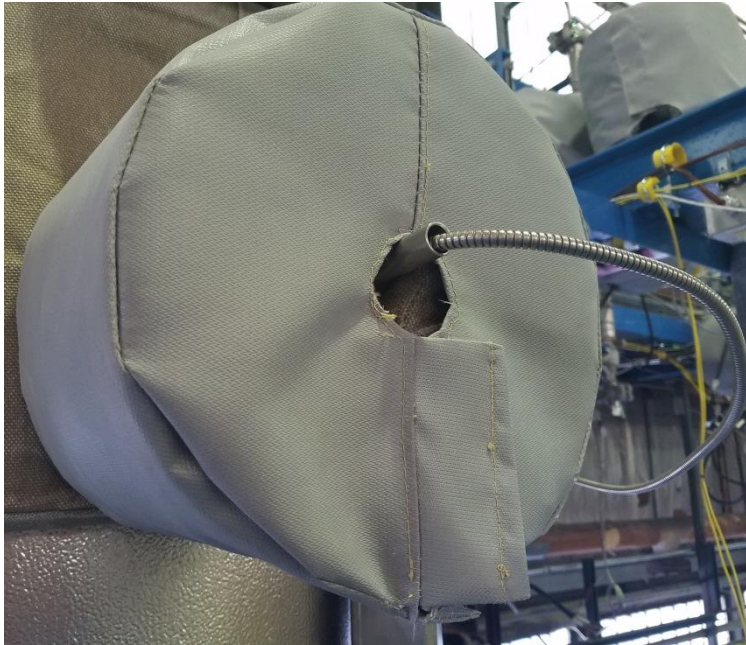
Figure 126 - Grayloc insulation jacket.

3.2.14.2 *Thermocouples*

Currently, all of the temperature measurements are made with type K thermocouples which have a standard limit of error of $\pm 0.75\%$ (Figure 127). The majority of the thermocouples are ungrounded, stainless steel sheathed and have a high temperature mini male connector. These thermocouples are strapped to the METL piping system and vessels. However, there are instances where the thermocouples' sheath is in direct contact with the working fluid. Currently, these occurances include the following:

- Cold Trap
- Plugging Meter
- Vapor traps for test vessels, expansion tank, and dump tank

Figure 127 – Over 500 Type K thermocouples and 10,000 feet of type K thermocouple wire were ordered for Phase I of the METL.

Thermocouples with their sheath in contact with sodium on the cold trap and plugging meter are welded directly into their respective component as these will experience a liquid sodium environment. The vapor trap thermocouples should only be exposed to sodium aerosols/vapors. Therefore, these are welded into a VCR fitting (Figure 128) which can actually be removed/replaced on the vapor trap.
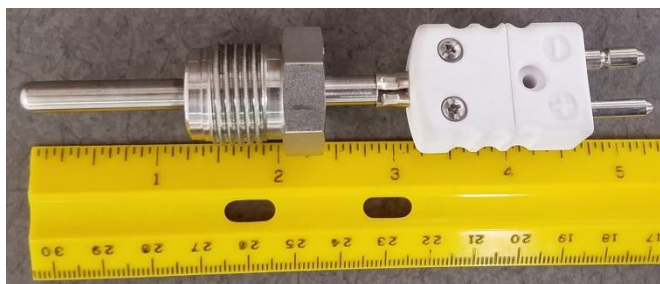
Figure 128 – In-flow vapor space thermocouple probe.

3.2.14.3   *Argon Volumetric Flow Controllers*

The argon cover gas flow into the vapor space of the vessels, expansion tank and dump tank needs to be controlled, so two independent mass flow controllers (Figure 129) were installed downstream of the argon regulator (Figure 89). The controllers are able to handle 1000psi and have a control range 1 – 300 lpm.

Figure 129 – Argon Mass Flow Controllers.

Similar Brooks mass flow controllers are installed near the dump and expansion tank. These miniature versions adjust the flow rate of Argon through their respective dip tube for the differential pressure level sensors described in section 3.2.5.2. These mass flow controllers can withstand a 1000 psig inlet and have a flow control of 3- 150 [cm^3/min]. A picture of the differential pressure level sensor and its mass flow controller installed for the dump tank is below in Figure 130.
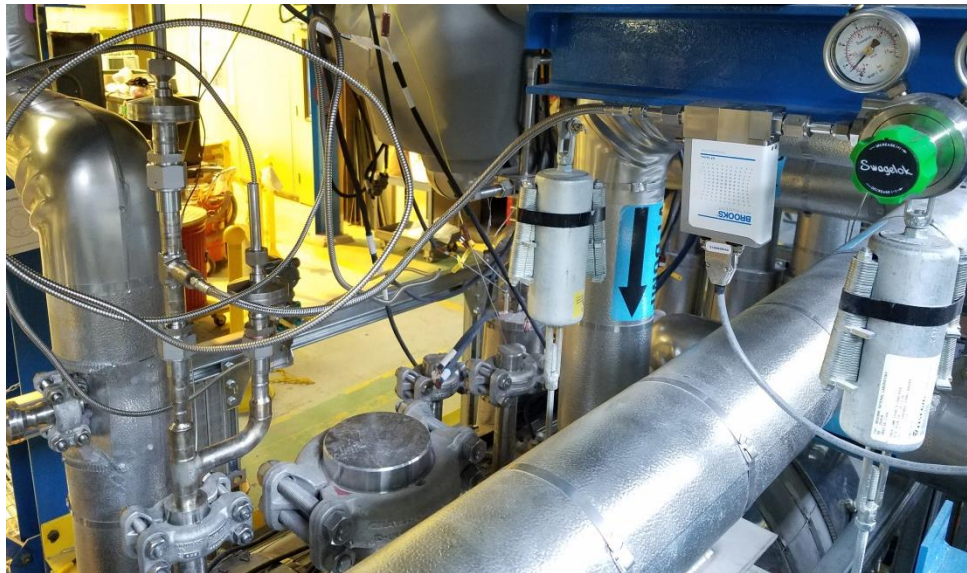
Figure 130 - Dump Tank Dip Tube Mass Flow Controller.

3.2.14.4   *Electric Meters*

Energy monitoring equipment was installed on all operational and experimental power for METL. Ten Schneider Electric METSEEM4928E meters were installed (Figure 131) to measure the current on all 342 heater zones used to operate METL as well as the total input power to every power enclosure. The power/energy monitoring will prove to be a useful diagnostic tool as well as allow the implementation of an algorithm to detect a run-a-way

solid state relay (SSR). Heater zones drawing a measureable current while having a PID MV value of 0 would indicate the SSR has failed closed (run-a-way) and then the control program could activate the shunt to open this circuit, protecting the equipment.

Schneider Electric PM8000 meters were installed on the power feed to the 3Φ 480 and 3Φ 240VAC panels that supply METL experiments with power. Although these meters lack the current transformer input count of the aforementioned meters, they offer the ability to measure total harmonic distortion to the 63rd harmonic. When new experiments are inserted into METL and brought online, information obtained from these meters can be used to determine if this experiment introduced any power quality issues. Lastly, measuring the total current draw of all experiments will ensure there is sufficient capacity to support any additional test apparatus.

Figure 131 - Electrical Meters and Current Transducers Installed in the Power Enclosures
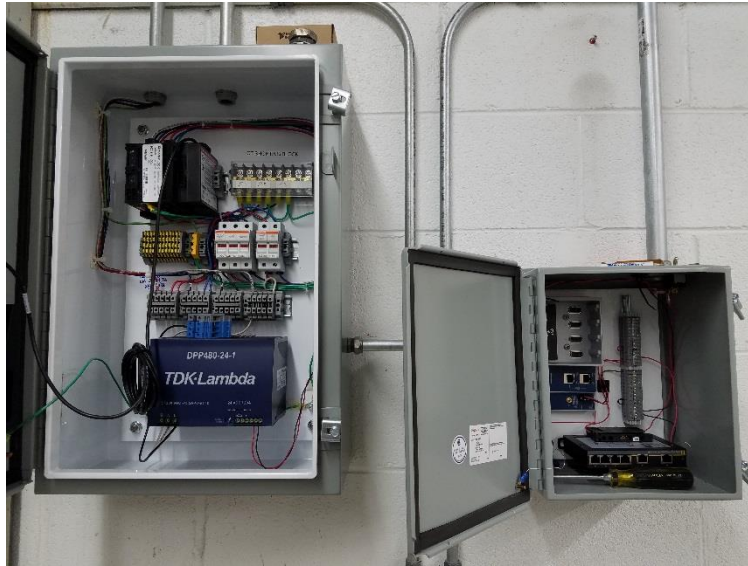
Figure 132 - Electrical Meter for Power Supply to Experiments.

3.2.15   *Quality Assurance*

3.2.15.1   *Heaters and Thermocouples*

Post-installation, the resistance of every heater and thermocouple was measured. The heaters were operated and thermocouple values read via control system to not only verify their operation but also ensure the controls were addressing the correct heater and thermocouple. A third round of heater and thermocouples quality assurance is currently underway.

3.2.15.2   *Vessels and Piping*

Although, 100% of the pipe welds were examined with X-ray and the vessels passed pressure testing; a helium leak test of the entire METL facility was conducted. Leaks discovered were due to mechanical fittings and have been corrected and all torque values were recorded. The location, force and configuration of all forty-three spring cans for Phase-I of METL was verified. Location of the threaded rod and shoe supports were confirmed as well. Missing spring cans or other supports were installed. Lastly, spring can block units were removed and the spring cans were adjusted to the proper cold force.

3.2.15.3   *Power Enclosure Conductors*

While applying terminal covers to equipment in the power enclosure, ANL-FMS electrical engineers discovered the power enclosure fabricator incorrectly used finely stranded cable (also known as Diesel Locomotive Cable) to make high current connections. Although the gauge of the conductor was appropriate for the current, the lugs on the circuit breakers were only rated for coarsely stranded cable. Using the improper strand density may result in a poor connection which ultimately could create an arc and damage equipment. In summary, all finely stranded cable in the power enclosures was replaced with coarsely stranded cable (Figure 133).
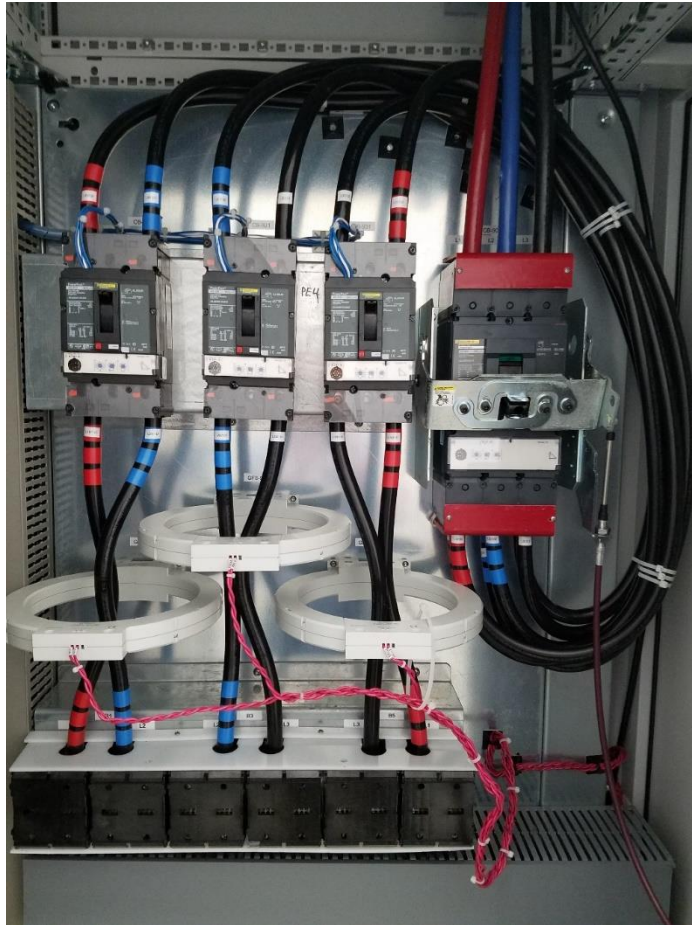
Figure 133 - Power Enclosure with Coarsely Stranded Cable.

3.2.15.4   Power Enclosure Terminal Covers

All of the equipment housed inside of the power enclosures (PE) was equipped with covers to shield personnel who enter the enclosure from coming into contact with metallic components (e.g. circuit breaker terminals) that carry high amperages. The majority of the covers were commercially available but some of distribution block and circuit breaker shields were custom. In summary, there is no shock hazard present in these enclosures as all high voltage components have a cover which by code does not require a worker to wear voltage rated gloves.

Figure 134. Power Enclosure with Terminal Covers Installed.

3.2.1   Commissioning

Prior to filling METL with sodium it was highly desired to operate as many components as possible up to their maximum limits to identify any present or potential issues. The initial heating up and commissioning of METL was one of the major activities in FY2018.

3.2.1.1 Thermocouple Noise

During function testing of every thermocouple and heater their performance appeared to be acceptable. However, during commissioning as additional heaters were simultaneously energized, thermocouple signals began to show signs of increasing noise. Through troubleshooting it was found that only thermocouples internal to the mineral insulated cable heaters were picking up noise on their signal. The quickest and successful solution implemented was a software approach to try and filter the noise as shown in Figure 135.

Figure 135. Noisy (left) and filtered (right) thermocouple signals

Utilizing a median filter with adjustable ranking, the noise was able to be rejected. Unfortunately, filtering requires a substantial increase in sampling which results in an undesired slow response. Therefore, hardware solutions were pursued in parallel such as adding resistors to the terminals of the thermocouples and adding low-pass filters (which had limited success). Upon further investigation it was found the thermocouple modules with internal cable heater thermocouples connected had a common mode range error. This led to the procurement of new thermocouple modules (Figure 136) that had isolated commons per thermocouple input. Utilizing the NI 9214 thermocouple modules proved successful but the 9214 module has half the channel count of the previous modules so reorganization of all 136 internal piping heater thermocouples was completed in FY18.

Figure 136. NI 9214 Thermocouple Module

3.2.1.2 Pipe Supports

METL's piping system was brought from ambient to 538°C and held at this maximum temperature for roughly a week. The piping was inspected to ensure it was not being restrained and had the ability to expand (the piping is actually designed to float). Minor issues were discovered such as shimming a few pipe shoe supports. The most significant finding

during the piping heat-up stage was a pipe support lug with a fairly short threaded rod (Figure 137) was causing a pipe shoe to lift off from its cantilever support and potentially restricting the piping system from growing. When the commissioning concluded and METL cooled, this support was replaced with a trapeze style to permit thermal expansion and allow the shoe to remain in contact with this support beam.

Figure 137 - Support Lug with Short Threaded Rod

3.2.1.3 Vapor Trap Heaters

Previously described in section 3.2.11.2 Vapor Traps & Filters, the vapor traps were originally heated with flexible cable or "shoe-string" heaters. Vapor piping, valves and the vapor trap were heated to 150°C during the commissioning period. All but one vessel vapor trap heater remained functional post-commissioning.

In contrast, the dump tank vapor trap was able to maintain this temperature throughout commissioning and did not show any signs of degradation indicating the "shoe-string" heaters should be replaced with a more suitable product. Therefore, as shown below in Figure 138, all of the vessel vapor traps were equipped with ceramic band heaters that provide 2kW of thermal power.
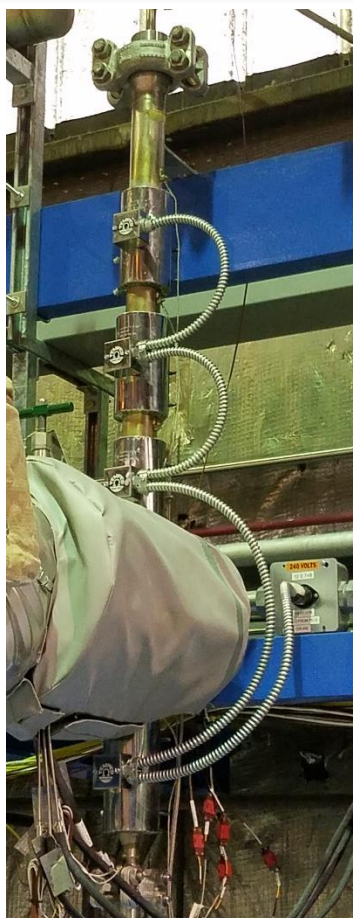
Figure 138. Vessel Vapor Trap with Ceramic Band Heaters Installed.

3.2.1.4 Swagelok Valves

During the commissioning of METL, it was observed that many of the Swagelok valves were calling for 100% heat and unable to maintain their set point. Many of the valve heaters internal element failed from constantly being energized. The primary cause was the lack of insulation as the Swagelok valves have many components that protrude from the insulation. Cerawool insulation was used to fill all of the voids to minimize heat loss and the back-up heaters were utilized to bring the Swagelok valve heaters to 538°C.

Post-commissioning, new Swagelok heaters and platens were installed. The new platen design allowed two heaters to be inserted (Figure 139) at a larger diameter so that the power density could be lowered thus decreasing required platen hole tolerances and reduced individual heater demand.

Figure 139. New Swagelok Heaters and Platens

The Swagelok valves were actuated post-commissioning but only minor valve stem movement was observed. Upon further investigation, it was revealed that the majority of the Swagelok valves were not fully opening and so efforts to determine the root cause was pursued with the manufacturer. A video of the valve operation was sent to the manufacturer who after viewing it deemed the cause was due to microscopic welding.

Some of these valves were not actuated during the commissioning process, this fact combined with the high temperatures caused, at a microscopic level, the valve tip to weld to the body. Swagelok instructed the METL team to exceed actuation pressures found in valve documentation and actuate the valves. This solution was effective as it broke the microscopic welds and the valves operated as intended at the design pressure. It should be noted, per the manufacturer, the microscopic welding is a normal event and did not compromise the valves longevity or ability to seal, future operations will involve actuating the valve during heat up/cool down to avoid the issue entirely. Also, it is acceptable to raise the actuation pressure as long as it does not exceed 150 psig.

3.2.1.5 Test Vessels

The Test Vessels were heated to 200°C and then held at this state as there was a large temperature gradient beginning to develop. The primary contributing factors to this temperature differential are believed to be:

- Insufficient heat by vessel support lugs (Zone 2)

- Deficient insulation

- Heat loss through support legs

The main protruding vessel features (support lugs and flexi-cask rest plate) are found in Zone 2 of the test vessels which makes it difficult to apply a heater. Upon further ANSYS simulations, it was shown that even applying a minimal amount of heat in this area would greatly reduce the thermal stratification of the test vessel. Custom tubular heaters were purchased to trace the unique geometry of the vessel and tack-welded to non-pressure boundary portions of the vessel to provide additional heat to this area. The effectiveness of these heaters will be tested during the next phase of commissioning in September 2018.

Figure 140 - Test Vessel Zone 2 Equipped with Tubular Heaters

Similar to the Swagelok valves, the insulation provided by the contractor proved to be insufficient and there were many voids in the test vessel insulation. METL crewmembers began assembling insulation blankets that could be inserted under the insulation jackets fabricated by the contractor. These blankets are shown on the flange of the test vessel in Figure 141 and are also used to fill in voids.

Figure 141 - ANL Fabricated Insulation Blankets for the Test Vessels.

Lastly, even with a thermal stand-off, the support legs provided a conduit for heat transfer and ultimately were not touch-safe while the vessels were only operating at 200°C. A support column for each vessel size was designed, fabricated and installed. Their performance will be evaluated during the second round of commissioning. If the new support columns resist a sufficient amount of heat transfer, the original support columns will be replaced by the new support columns.

3.2.1 *Experimental Support Infrastructure*

In anticipation of operating test apparatus in METL, some infrastructure required to operate experiments has been installed such as a dedicated argon gas and electrical supplies designated solely for the METL test articles.

3.2.1.1 Electrical

Due to METL providing the resource intensive liquid sodium environment, the majority of experiments are not expected to have large power requirements. The fused disconnects in Figure 142, supply 100A of 2Φ 240VAC power. This is expected to be the most frequently used resource (other than liquid sodium) by experimenters as this is sufficient power to energize a data acquisition system, valves, small motors and other instruments. Also, the disconnects can have lower current rated fuses installed, decreasing the capital cost and engineering design required for smaller experiments.

Figure 142 - Fused Disconnects for 2Φ 240VAC Power Supply to Experiments

The anticipated first experiment for METL is the Gear Test Assembly (GTA) which aims to evaluate the performance of Inconel spur gears immersed in an 18-inch test vessel full of sodium. This device requires these gears to be driven by two 480VAC 3Φ motors. Accommodations for the GTA have been completed and are shown below in Figure 143.

Figure 143 - 3Φ 480VAC Power Supply for Experiments.

The equipment above consists of a 200A disconnect that feeds a 3Φ 480VAC circuit breaker panel which energizes two delta-wye transformers and a 100A fused disconnect. The delta-wye transformers supply energy to the GTA motors and act as an isolation device. The fused disconnect is available for future experiments and like the 240VAC power, the 480VAC fuses can be replaced with lower current rated ones for smaller experiments.

3.2.1.2 Flexi-Cask System

When test articles are installed or removed there is a possibility that air could contaminate sodium that is frozen to the experiment or vessels. To limit the risk of air contamination, a flexi-cask system will be used to provide an inert atmosphere for the vessels and test articles.

As shown below in Figure 144, the flexi-cask system is lowered onto the vessels. The volume within the flexi-cask is kept inerted using a constant argon purge. The flexi-cask system will operate using the pre-existing crane in the Bldg. 308 high bay, as shown in Figure 145. During FY2015, the design of the flexi-cask was completed and the contract to fabricate the flexi-cask was awarded to an outside vendor.
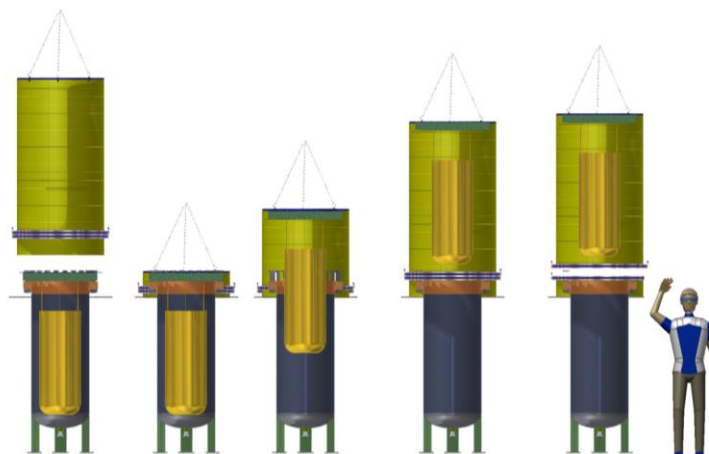
Figure 144 – A 3D model depicting of flexi-cask operation.
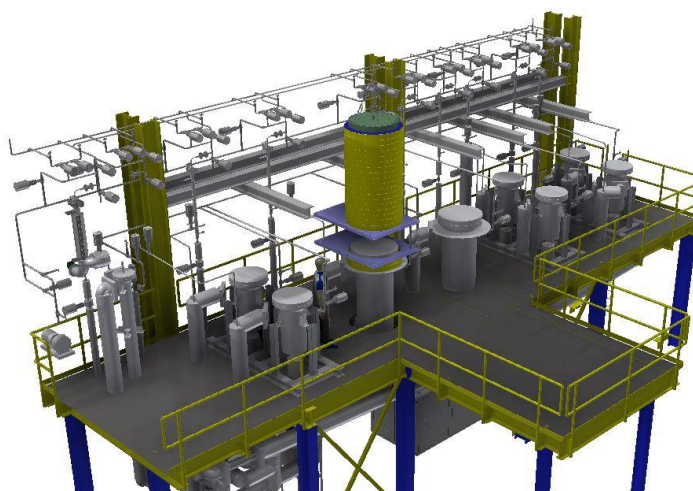
Figure 145 – A 3D model showing how the flexi-cask system will operate above the METL facility.

The flexi-cask required some minor modifications once received from the outside vendor. These alterations were performed by ANL-CS and the flexi-cask assembly has been completed. Initial tests to measure the flexi-casks ability to retain argon gas during different scenarios have been conducted.

Figure 146 - Flexi-Cask Demonstration in Qualifying Station

The flexi-cask rest plate diameter of the test vessels was reduced to alleviate excessive stress that would occur when heated. However, the smaller diameter rest plate could no longer support the flexi-cask. Therefore, extensions to the rest plate were designed and fabricated to be installed while the vessel is cold so the flexi-cask could be used and then removed once the vessel is ready to be heated. A rest plate extension installed versus the permanent rest plate is illustrated below in Figure 147.

Figure 147 - Vessel Rest Plate Extension

3.2.1.3 Carbonation System

When components are removed from METL, they will be covered in frozen sodium residue. In order to safely and gently react away the unwanted sodium, the components will be cleaned using a mois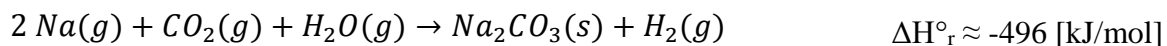t carbonation system. This process was originally developed by Argonne several years ago for the EBR-II deactivation program.

The P&ID of the carbonation system that has been built at Argonne can be found in Figure 148. The carbonation system consists of a CO_2 bubbler and reaction chamber. First, a column of water is heated just below its boiling point ($\approx$90°C). Then dry carbon dioxide is pushed through the bottom of the water column to create humid carbon dioxide at the top of the column. Humid carbon dioxide travels through a transfer line in order to carry trace amounts of moisture into the reaction chamber containing the used test articles. The moisture and CO_2 react with the sodium residue in one of the two following processes:

$$Na(s) + CO_2(g) + H_2O(g) \rightarrow NaHCO_3(s) + 0.5\ H_2(g) \qquad \Delta H°_r \approx \text{-313 [kJ/mol]}$$

$$2\ Na(g) + CO_2(g) + H_2O(g) \rightarrow Na_2CO_3(s) + H_2(g) \qquad \Delta H°_r \approx \text{-496 [kJ/mol]}$$

Figure 148 – A P&ID for the carbonation system. (M = manual valve, S = solenoid valve).

Figure 149 – A photo of the completed bubbler for the carbonation system. Carbon dioxide enters through the bottom of the system. Electric heaters are used to raise the temperature of the water to facilitate increasing the humidity of the water.

Reaction chamber supports along with the chamber itself were installed in FY18. The carbon dioxide bubbler was installed on the NSTF mezzanine in B308 and a transfer line was installed connecting the bubbler to the reaction chamber. Lastly, the control system was revitalized to support autonomous operation.

Figure 150 - Reaction Chamber (left) Connected to Bubbler (right)

3.2.2   METL Sodium Fill

Fifteen 180 [kg] drums of R-Grade (99.9%) sodium was transferred into the METL Dump Tank in FY18. This was achieved by applying three band heaters to the outside of a sodium drum and then wrapping it with removable insulation blankets as shown in Figure 151. Bung connections were threaded into the drum and argon gas was supplied to the drum to provide a cover gas for the solid sodium.

Figure 151 - Sodium Drum with Heaters and Insulation

The following morning, the heaters were energized and the temperatures/pressures were monitored via Sodium Fill program (Figure 152). Concurrently, METL crewmembers operated the scrubber and superheated steam system to burn and dispose of the sodium heel from the drum transferred the previous day. Once the sodium drum was near 130°C, it was prepped for transfer. It took roughly 8 hours to bring a full drum of sodium from ambient to 130°C.
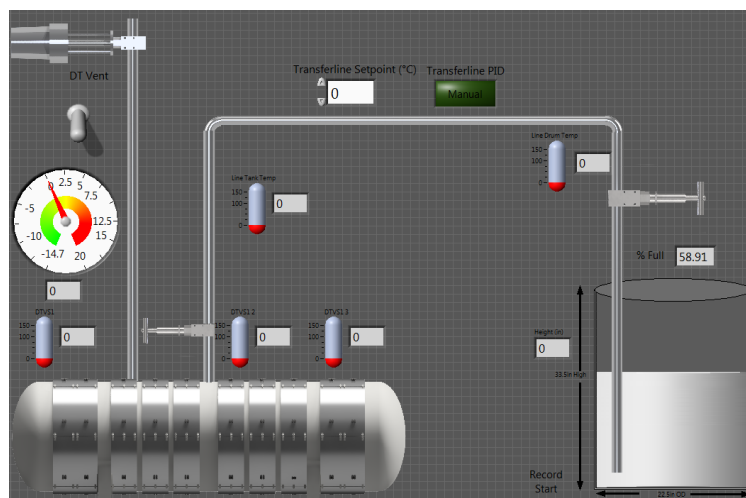
Figure 152 - Sodium Fill GUI

Pressure inside of the drum was relieved, a dip tube was inserted into the drum and the transfer line was connected to the dip tube. Pressure was then reapplied to the drum. When the transfer line reached a temperature ≈ 150°C, transfer line valves were opened to allow argon gas to push sodium through the dip tube/transfer line and into the dump tank. The actual transfer process varied between 1 and 1.5 hours. Summarizing, it required a minimum of 10

hours to transfer one drum of sodium so a drum was emptied per day over the course of three weeks.

The final outcome was the transfer of 750 gallons of sodium into the dump tank which equates to a height of thirty-four inches. The average transfer temperature was 139°C which corresponds to a sodium purity of 1.46 ppm oxide. The Dump Tank heaters were then turned off and the dump tank isolated to allows the sodium to cool and freeze. After the sodium was frozen, corrections of various punchlist items continued before operations in METL were resumed.

3.3 Building 308

3.3.1.1 Roof and Exterior

During FY2015, a new waterproof membrane was installed on top of the Bldg. 308 high bay by Roofs Inc. Additionally, the exterior of the high bay was repainted with a weather-proof epoxy. The total cost of the work was over ~ $1M. Senior lab management fully supports the experimental work being conducted in Building 308.

Figure 153 - A photo of the Bldg. 308 hi-bay. During FY2015 a new waterproof membrane was installed over the preexisting roof and the exterior of the building was repainted with a weather-proof epoxy.

3.3.1.2 Lifeline

Components that seldom require maintenance or human interaction were placed in elevated locations to prevent them from becoming future obstructions. However, it was still desirable

to safely access these parts so a horizontal life line was installed with three retractable lanyards to allow METL crewmembers to work at these heights. Shown in Figure 154, the lifeline spans the width of the METL mezzanine in the B308 high-bay.

Figure 154 - B308 High-Bay Lifeline

4 Summary

The preceding report provided a summary for the status of the METL facility as of August 2018. A tremendous amount of effort has gone into the commissioning activities of the Phase I configuration of METL. A special focus of FY2018 was finishing METL fabrication, commissioning the system, troubleshooting, correcting the issues found and preparing for operations. Procurement of remaining METL Phase-I systems and components will continue into FY2019, along with the experimental test components and systems.

In early September 2018, the METL facility is being reheated to initiate initial system fill from the dump tank and start of initial sodium purification in METL. The facility is expected to be fully operational and will begin testing in early FY2019.

5 Bibliography

1. **Liquid Metal Engineering Center.** *Liquid Metal Level Measurement (Sodium) State-of-the-Art-Study.* 1968. NAA-SR-Memo-12582.

2. *A General Equation for the Solubility of Oxygen in Liquid Sodium.* **Noden, J. D.** 1, s.l. : Journal of the British Nuclear Energy Society, 1973, Vol. 12, pp. 57-62.

3. **Hvasta, M. G.** *Designing & Optimizing a Moving Magnet Pump for Liquid Sodium Systems.* s.l. : University of Wisconsin - Madison, 2013. PhD Dissertation.

4. *The dynamic characteristics of a plugging indicator for sodium.* **McPheeters, C. C. and Biery, J. C.** s.l. : Nuclear Applications, June 1969, Vol. 6, pp. 573-581.

5. **Jackson, C. B.** *Liquid Metals Handbook: Sodium-NaK Supplement.* s.l. : US Atomic Energy Commission, 1955.

6. **Department of Energy.** *NE Standard: Vapor Trap Assemblies for Sodium Service Including Amendments 1 and 2.* 1974. NE E 4-14T.

7. **Gems Sensors and Controls.** *XT-1000 Magnetostrictive Level Sensors (Brochure).* 2013.

8. **Westinghouse Hanford Company.** *Liquid Metals Fire Control Engineering Handbook.* Hanford, WA : s.n., 1979. p. 94.

9. **Argonne National Lab.** *Testing Infrastructure and Needs for the Advanced Recycling Reactor.* s.l. : Global Nuclear Energy Partnership.

10. **Sherman, S. R.** *Technical Information on the Carbonation of the EBR-II Reactor.* s.l. : Idaho National Laboratory, 2005. INL/EXT-05-00280.

11. **Graczyk, D.** *14-0125 Report.* s.l. : ANL, 2014.

12. **Kultgen et al.** *ANL-ART-73, ANL-METL-9.* ANL, 2016.

13. **Hvasta et al.** ANL-ART-24, ANL-METL-5. ANL, 2015.

14. *Methods for the Analysis of Sodium and Cover Gas.* RDT F-3-40-T:1793. U.S. Atomic Energy Commission

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